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# OBSERVATIONS OF NOCTILUCENT CLOUDS

*Ch. I. Villmann, Editor*

*"Nauka" Press, Moscow,* 1967

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# OBSERVATIONS OF NOCTILUCENT CLOUDS

Ch. I. Villmann, Editor

Translation of "Nablyudeniya serebristykh oblakov"
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## PREFACE

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Noctilucent clouds are a rare and, at the same time, very interesting natural phenomenon which has recently attracted the attention of researchers in different countries, specialists in various fields of knowledge, and amateur observers. The International Symposium on Noctilucent Clouds which took place in the spring of 1966 in Tallinn indicated the great interest which exists. Representatives of 11 countries, including geophysicists, astronomers, meteorologists, and physicists participated in this symposium.

The distinctive characteristics of noctilucent clouds are their height above the Earth's surface (about 80 km), the strict latitudinal and seasonal limitations on their appearance, their fine structure, the large areas of the cloud fields, and, at the same time, their almost absolute transparency.

Noctilucent clouds were first discovered as an independent natural phenomenon in Russia (by V.K. Tseraskiy, in 1885). The first systematic studies of noctilucent clouds were begun in the Soviet Union, and we were the first to set up a network of stations for observing them, thus successfully dealing with the problems of the theory of their formation.

This collection, which was prepared by the All-Union Astronomical and Geodetic Society, contains articles which examine both theoretical problems and the results of the observations of noctilucent clouds conducted in the USSR according to the program of the Division of Noctilucent Clouds in the Central Council of the All-Union Astronomical and Geodetic Society. /4

The publication of these studies will undoubtedly expand our knowledge of the nature of noctilucent clouds themselves, as well as related cloud formations on Mars and Venus. It will also bring about a deeper understanding of the processes occurring in the mesopause of the Earth's atmosphere and the atmospheres of the terrestrial planets.

# FOREWORD /2

This collection contains articles which examine the nature and the results of observations of noctilucent clouds floating at an altitude of 80 km. The themes of the articles include a survey of observations of noctilucent clouds after 1950, a theory of wave movements in noctilucent clouds, methods for determining their position in a projection on the Earth's surface, calculations of the coordinates of the clouds with the aid of electronic computers, the results of observations of noctilucent clouds in Latvia, Estonia, and the Smolensk and Ryazan regions, and the problem of linking the appearances of noctilucent clouds with atmospheric currents on the Earth and with sunspot activity.

The collection was intended for specialists in geophysics, meteorologists, astronomers, graduate and undergraduate students, and amateur astronomers.

Editor-In-Chief,
Candidate in Physical and Mathematical Sciences
Ch. I.Villmann

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# MORPHOLOGICAL ASPECTS AND THE NATURE OF NOCTILUCENT CLOUDS

N.I. Grishin

*ABSTRACT: The morphological aspects and the nature of noctilucent clouds are discussed in this article. The author shows the principal advantages of time-lapse photography in examining the wave movements in the clouds and in determining the nature of the upper layer of the clouds and the lower layer, or the veil. It is shown that the chemical composition of the condensed material in noctilucent clouds should be studied in greater detail, and that water vapor should not be considered the only possible substance comprising the condensed part of noctilucent clouds.*

Morphological studies of noctilucent clouds have been conducted /5* since their discovery. Such morphological descriptions were made even in 1885-1886. However, interest in them soon waned, and these clouds were treated only as a curious phenomenon for more than half a century. Single reports and studies of them appeared from time to time in periodicals. However, there was no subsequent scientific accumulation of the observational data. Nevertheless, the latter are necessary as the first link in studying any natural phenomenon.

## Organization of Regular Observations

The first attempt in the USSR to organize scientific observations of noctilucent clouds was made by Ye.L. Krinov in 1935. His directions for regular observations [1] were the first experiment with such instructions, and they stimulated amateur observations.[1] However, studies on a professional level remained insignificant. In 1937 and 1939, instructions for observing noctilucent clouds were drawn up by G.O. Zateyshchikov and V.A. Bronshten [2]. New directions made by V.A. Bronshten appeared in another edition ten years later [3].

A systematic series of regular observations was begun in 1949. V.G. Teyfel' (in Rybinsk) and N.I. Grishin (in Moscow) accumulated data in order to develop a unified method for scientific observa-

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*Numbers in the margin indicate pagination in the foreign text.

[1]The earliest attempt to draw up instructions for observations of noctilucent clouds was made by K.D. Pokrovskiy [66].

tions of noctilucent clouds. Different variations were tested for several years. The observational data served as the basis for a number of new studies. These studies included a work which attempted a morphological classification of noctilucent clouds [4]. /6 It was based on the data of numerous visual and photographic observations. The cinematographic materials helped in making certain details of the classification more accurate. The principle of the common nature of geometric, dynamic and other physical properties characteristic of the shapes of noctilucent clouds was the underlying concept. The number of works examining various aspects of the nature of the phenomenon increased simultaneously [5, 6]. Thus, there arose the need for conducting more expansive observations and measurements.

At the beginning of the International Geophysical Year (1957-1958), the All-Union Astronomical and Geodetic Society (AUAGS) of the Academy of Sciences of the USSR worked very industriously on a formulation of the scientific problem of noctilucent clouds. At the second session of the AUAGS, it was resolved in a special report [7] that this society would participate actively in the IGY program in terms of the problem of noctilucent clouds [8]. The program for these studies was soon established [9, 10]. This program stipulated that composite observational data on the principal physical properties of noctilucent clouds should be obtained during the course of the IGY.

During subsequent years, the AUAGS has participated actively in the programs of the IGY, the IGC (International Geophysical Cooperation of 1959), and the IQSY (1964-1965). The observation stations of AUAGS are established as the standard; the data of these stations are most reliable, and are used as the reference sources. The first scientific conference on the problem of noctilucent clouds was organized by the AUAGS and held on December 1-2, 1965 in Moscow [11]. The conference unified different researchers who had been studying the problem. The Joint Geophysical Committee for executing the IGY program established a special working group for studying noctilucent clouds; this group did a large amount of work in organizing the observations during the IGY period. Shortly after this, 220 stations of the Central Board of the Hydrometeorological Service of the USSR were conducting regular observations, for which a special program, instructions, and outlines for logging the observations were drawn up [12, 13].

Before the beginning of the IGY, the All-Union Astronomical and Geodetic Society held a second scientific conference on noctilucent clouds. A large number of scientific research establishments had been included in the study by this time: the Astronomical Observatory of Leningrad University, the Institute of Applied Geophysics of the Academy of Sciences of the USSR, and Ural State University (in Sverdlovsk). Instructions for observation of noctilucent clouds were drawn up by N.I. Grishin, particularly for the IGY program. These instructions were accepted as the international

standard, and were reprinted in Belgium in French [14]. On the basis of these instructions, several manuals for observations of noctilucent clouds were published in the USSR [15-18]. These /7
manuals included those published in Latvia (by M.A. Dirikis) and in Estonia (by C.I. Villmann). Noctilucent clouds became the subject of an international coordinated study. Periodic scientific conferences discussed the problems of the methods for observations and the results of experimental and theoretical studies. To the present, eight such conferences have been held (see Table 1).

TABLE 1

| No. (in seq.) | Date | Site of the Conference | Principal Theme | Publications |
|---|---|---|---|---|
| 1 | 1–2.XII 1956 | Moscow | Preparing for IGY | [11] |
| 2 | 9–10.IV 1957 | Moscow | Program for Studies during IGY | [19] |
| 3 | 27–28.III 1958 | Leningrad | Results of the 1st Year of the IGY | [64] |
| 4 | 12–14.XII 1958 | Tartu | Results of the IGY | [20]; Works of the Conf. [21][65] |
| 5 | 23–26.IV 1959 | Sverdlovsk | Results of studying Noctilucent Clouds in the Urals | [65] |
| 6 | 22–24.X 1959 | Riga | Nature of Noctilucent Clouds | [22]; Works of Conference [23] |
| 7 | 16–19.V 1961 | Tallin | Results of the Studies of the IGU | [24, 25]; Works of Conference [26] |
| 8 | 13–15.V 1965 | Tartu | Results of the Studies during the IQSY | [27] Works of Conference [28] |

Documentary observation data began to appear regularly. Almost every appearance of noctilucent clouds was photographed many times. Time-lapse photography was used. In the divisions of the AUAGS (Latvia, Estonia, Leningrad, Smolensk, Moscow, Ryazansk, Gor'kiy, Ulyanovsk, Sverdlovsk, Novosibirsk, and Tomsk), many tens of thousands of photographs and other documentary materials have been accumulated. Nevertheless, these materials have not been analyzed in sufficient detail. There have not been enough articles on the results of an analysis of concrete observations and measurements. At the same time, the theoretical studies need much more factual materials. There is even a certain gap between the theoretical studies and the observational data, of which there is not enough to substantiate the theoretical studies.

This also concerns the morphology of noctilucent clouds. Many of the physical and chemical processes appear in external form, i.e., in the shape, brightness, and dynamics of these clouds. Therefore, the morphological studies are important source materials for subsequent examinations of the nature of the phenomenon on the whole. The methods and means of a morphological study are constantly being improved. Visual observations were converted into documentary photographic recording of the phenomenon. Time-lapse photography has greatly expanded the possibilities of researchers [29]. Laser sounding of noctilucent clouds is beginning to be used [30]. The American and Swedish experiments with rocket sounding of noctilucent clouds are well known for their interesting results. We can now look forward to automation of massive measurements of the heights of various morphological formations. The stereo photography proposed by C.I. Villmann [30] will be an excellent solution to this problem. We will now examine certain aspects of morphological studies in relation to the contemporary problems posed by noctilucent clouds. /8

## Waves in Noctilucent Clouds

The wave processes in the mesosphere play a very important part in the physical nature of noctilucent clouds. The atmospheric waves seem to be blocked by a thin film of clouds. The waves move in definite phases [29].

We are accustomed to observing waves in water from above. Clouds are observed from below (from the Earth's surface), and this

Fig. 1. Part of a Field of Noctilucent Clouds with III-a and III-b Wave Formations. The Photograph was Rotated 180°. The Black-and-White Band Blurs the Points where the Wave Surface of the Clouds and the Vertical Plane Intersect.

usually prevents distinguishing wave formations in them. Therefore, it is more convenient for calculations and analyses to rotate a photograph of noctilucent clouds in the plane of the image by 180°, i.e. to turn it upside-down. Nothing is substantially changed by this. The same side of the cloud layer (turned toward the Earth's surface) is being viewed, but the physiological conditions are more advantageous for discovering the disturbance in the cloud layer. This method greatly simplifies morphological calculations of the photographic materials. The altered position of the photograph is also advantageous in terms of the fact that the parts of the clouds which are closer to the observer are in the lower part of the print. The objects furthest away are in the uppermost sections of the photograph. This corresponds to the appearance of the relief of the Earth's surface to which we are accustomed. Figure 1 shows an example of the wave field of noctilucent clouds which has been turned by 180° in the plane of the image. The black-and-white strip in the photograph was plotted according to the line of intersection between the cloud layer and the vertical plane. The strip marks the relief of the cloud layer more graphically. We can clearly see

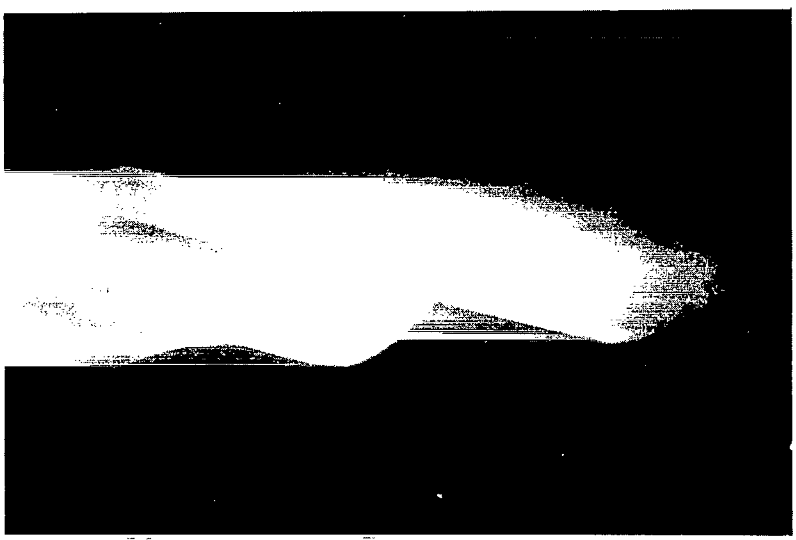

Fig. 2. Model of a Typical Wave of Noctilucent Clouds.

two waves of III-b type and many waves of III-a type.[2]

The wave deformation of the cloud layer brings about a change in its apparent brightness. The photometric contour of a cross-section of the cloud wave changes, depending on the orientation of the wave elements in relation to the observer. Figure 2 shows a model of a typical wave in noctilucent clouds. In another article [31], we examined the optimum example of an observation of a layer of noctilucent clouds at an angle of 15°. Under actual conditions, there are various angles of observation of a wave surface. The line of sight can traverse one layer of clouds at right angles or less to its surface. A change in the length of the path of the line of sight inside the clouds obviously changes its apparent brightness. It follows from Figure 2 that the line of sight can even pass three times through a cloud layer distorted by a wave. This effect of an overlapping of three cloud layers is clearly visible in Figure 1. /9

It is particularly difficult to distinguish a wave formation whose front is perpendicular to the line of sight. The wave is concealed to a greater degree if one inclined surface is parallel to the line of sight; in this case, the characteristic markings of a wave shape disappear. Outwardly, this type of wave most resembles a band (stream). Figure 3 shows a photometric cross section of this wave from the standpoint of the observer. The brightness of a part of the cloud field decreases rapidly. It sometimes seems that a dark zone with no clouds is in the immediate vicinity of the

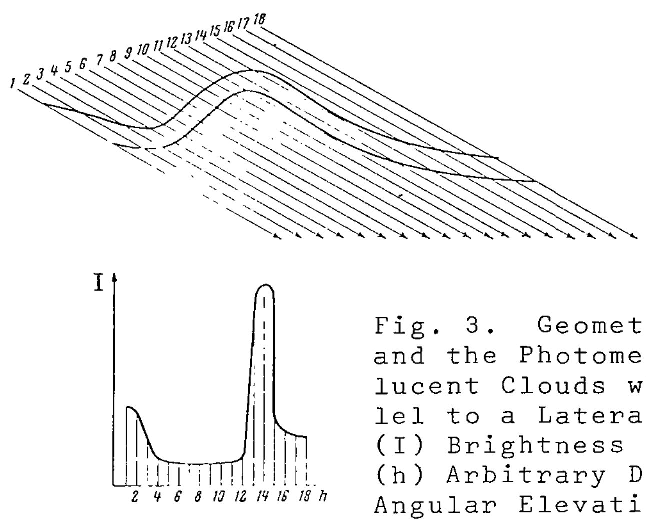


Fig. 3. Geometric Conditions of Observations and the Photometric Contour of a Wave of Noctilucent Clouds when the Line of Sight is Parallel to a Lateral Inclination of the Wave. (I) Brightness of the Cloud in Arbitrary Units; (h) Arbitrary Distance Coinciding with the Angular Elevation above the Horizon if the Front of the Wave is Parallel to the Horizon.

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[2]Since the morphological classification has become international, we will use Latin letters (instead of Russian ones) for the abbreviated notations.

bright band. Some researchers have thought that this is a shadow cast by a denser cloud section. The substantial decrease in brightness can be explained by the change in the inclination of the cloud layer relative to the line of sight. In Figure 3, Rays 4-12, which /10 are almost perpendicular (to the element of the cloud layer) penetrate a thinner layer of clouds than do Rays 1-3 and 15-18 of the cloud background. Therefore, a characteristic dark space is observed in the zone of Rays 4-12 in front of the bright band. This can be explained by the fact that the optical density of the clouds is extremely low. Only Rays 13-14, which enter the cloud layer at a small angle, traverse a long path inside the wave element of the clouds. The apparent brightness increases rapidly, and subsequently decreases rapidly. As a result, the observer perceives a contrasting, sharply marked, narrow and bright band. If a new wave does not follow this "band", then the apparent brightness of the cloud background does not decrease to the level of the dark zone in front of the bright "band". Such a photometric contour of a wave formation is often observed visually, and is clearly noticeable in photographs.

If the inclined side of a high and sharp wave is not parallel to the line of sight, the result is the type of photometric cross section shown in Figure 4. Rays 9-12 pass through the distorted cloud surface three times. The total length of the line of sight in the cloud greatly increases in the region of Rays 7-14. A decreased brightness of the cloud field is observed in the region of Rays 3-6. In a formal photometric analysis, a twofold brightness maximum can lead to a false belief in the existence of two waves. It is particularly important to keep this in mind during an automatic analysis of the photographs to study the spectral (statistical) distribution functions of the wave formations in noctilucent clouds.

The diversity of the variations in the location of different waves relative to the observer produces the multiplicity of their photometric contours in noctilucent clouds.

The morphological picture rapidly changes as a result of the /11 continuous movements of these wave formations. Moreover, the same

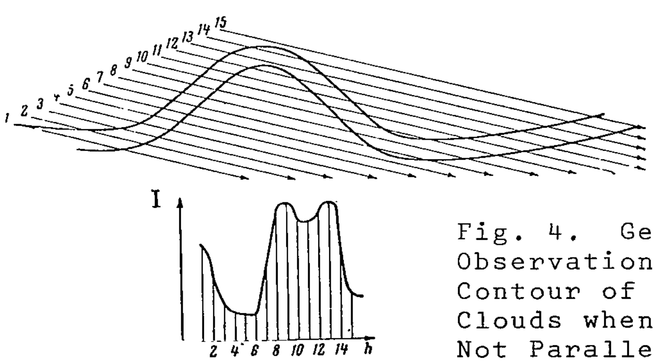


Fig. 4. Geometric Conditions of Observations and the Photometric Contour of a Wave of Noctilucent Clouds when the Line of Sight is Not Parallel to a Lateral Inclination of the Wave.

details can have different appearances in relation to the distance to the observer and in relation to the geometrical conditions for their illumination by the Sun from below the horizon. The geometrical structure of a cloud field can sometimes change so greatly in 10-20 min that no trace remains of the previous formations; everything has been replaced by new structural forms. It is often difficult to identify the same wave crests in photographs obtained 2 or 3 minutes later; the analysis becomes indefinite or simply impossible.

This complication was overcome by the method of dynamic photographic recording of a phenomenon. Since 1953, we have been using a special method of time-lapse photography of noctilucent clouds [32]. The documentary photographic materials have a system of precise time markings and geodetic coordinates on each frame. Time-lapse photography has made it possible to study the morphological and dynamic nature of noctilucent clouds. The wave nature of such formations was discovered by this method; it was previously considered that this was the product of a channelled atmospheric current. A combined analysis of the photographic materials and a series of large-scale photographs has greatly simplified interpretation of the dynamic regime of various morphological formations; this aids in a correct understanding of the local changes in the brightness of the clouds. In analyzing photometrical measurements, it is necessary to distinguish a real thickening of a cloud mass per unit volume from an apparent thickening, which is the result of a superposition of several cloud layers along the line of sight.

Figure 5 gives an example of a wave field of noctilucent clouds observed at Zvenigorod on July 20-21, 1954, at 0057 local time. The location of two types of waves (III-a and III-b) was determined according to the photographs and given in a projection on the Earth's surface within the limits of the plane for the figure. The average length of the III-a wave was equal to 8-10 km. The rate of the movement from NNE to SSW averaged 50 m/sec. The other group of waves (III-b) had a length of 20-30 km and moved from SE to NW at an average velocity of 30 m/sec. As we can see from Figure 5, there are deviations in the average wavelength values by ± 20%. The rates of the wave movement show the same divergence from the average values. The directions of the movements within this field deviate from the average by ± 10°. Figure 5 shows a typical example of a superposition of two wave systems over one layer of noctilucent clouds. These waves were observed for 3 hours. Their mutual position and direction of movement remained constant, as a rule. The wavelength and the rate of movement of the waves changed with time for each group. It is interesting that the III-a and III-b waves at this site had a roughly identical length (7-8 km) and /12 average rate of movement (15-20 m/sec) during the initial period (23.40). During the initial period, the noctilucent clouds had a small, localized area of dispersion and a poorly developed structure which was mainly veiled. Subsequently, wave shapes predominated; the brightness and the area of the clouds increased substantially. With the approach of morning, the clouds did not disintegrate, but gradually lost their contrast as the brightness of the sunrise background increased. Can they exist during an entire day? The appearance of already well-developed noctilucent clouds during the early evening [33] seems to indicate that they had been forming for a long time before twilight. However, a complete solution to this important problem of the physics of cloud formations in the mesosphere can be realized only by observing them during the day (for example, on board a high-altitude aircraft, when there is no interference from the blue background of the daytime sky). /13

The predominance of wave processes is a characteristic feature of noctilucent clouds. Morphological studies have shown that there is a broad spectrum of wave formations in them [34]. Classifications have distinguished three types of waves: Type III-a includes the shortest waves (from 2-3 to 10-15 km). Their amplitude is within

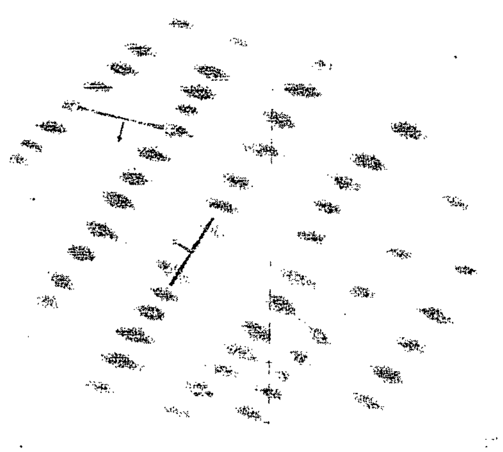

Fig. 5. Projection of a Part of a Wave Field in Noctilucent Clouds Observed on July 20-21, 1954 on the Earth's Surface (Negative). Within the Limits of This Projection, the Earth's Surface is a Plane. The Vertical Axis Shows the Direction toward the North and the Distance from the Observation Site in Kilometers. The Horizontal Axis Shows the Value of Digression to the Right and the Left from the Axis of the Distance in Kilometers.

the limits of 2-5 km. They can be distinguished by their particular mobility. The propagation rate of these waves varies from 10-20 to 50-70 m/sec. Type III-b includes the waves with lengths from 15 to 30-50 km. The propagation rate of the fronts of such waves can be assumed to be 10 to 100 m/sec.

The III-a and III-b waves, obviously, have a similar nature. They are often present simultaneously in one layer of clouds, interweaving and forming a so-called lattice. Depending on their distance, it is sometimes very easy to confuse them. Usually, the larger III-b waves have waves of III-a type in elements of their surface.

The period of oscillation of these waves is short. It is measured as several minutes for III-a type, and as 10-20 min for III-b type. The rising and falling movements of individual segments of a wave surface are determined by the amplitude and period of the wave. Figure 6 shows a change in the height of certain segments of a wave surface with III-a and III-b waves as a function of time; the measurements were made by M.A. Dirikis, S.V. Yevdokimenko, and Yu. L. Frantsman [35]. These authors did not present photographs which showed concrete points in the segment of noctilucent clouds they were measuring, but only related the types of waves measured. We can see from Figure 6 that some of the points tend to move upward, while others tend to move more or less abruptly downward. The vertical and horizontal velocity components for these points are given in Table 2. The resulting velocity vector corresponds to the angle of inclination of the cloud surface along which the visible shift of the measured point occurred. This angle, obviously, is the local slope of the wave surface. The authors did not describe their methods for selecting the points for which the heights were measured. Apparently, they selected the most noticeable segments of the cloud which preserved their markings and were identifiable in several subsequent photographs. During the process of natural wave movement, or during the process of being carried away with the supporting wave surface, these segments change their markings and brightness. At a certain moment, they /14
disappear from view because of the reasons mentioned earlier (see Fig. 1-4). Thus, for a number of methodological and physical reasons, it is impossible to conduct direct measurements of an entire cycle of a wave movement by the regular methods. Therefore, only certain parts of the phases of the wave movements of noctilucent clouds are given in this example.

Moreover, when time-lapse photography is not used, it is very difficult to "filter out" the interweaving wave oscillations in various directions. As a result, it is the total velocity of combined points for two or more waves with different directions, and not the phase velocity of one wave, which is being measured. The resultant velocity vector, obviously, can be both greater and less than the vector components. Therefore, the measurements in [35] show the magnitude (see Fig. 6) and the velocity (see Table 2) of a phase oscillation of part of the cloud layer only at combined points. We can obtain a representation of part of the total amplitude of the wave oscillations from these data. The angles of inclination of the cloud surface along which the measured points moved are also given in Table 2. In the columns labeled "vertical velocity" and "angle of inclination", the plus sign means a rising movement and the minus sign means a falling movement. Points 1-4 refer to small waves of III-a type [35]. One of these moved downward, and the other three moved upward. The total range of heights to which they moved is between 80.5 and 87.5 km (see Fig. 6). The amplitude of the III-a waves is usually two times less than that /15 range. This means that these waves were on the surface of waves of III-b type and that in addition to their inherent oscillation, they took part in the movement of the wave supporting them. Some III-b waves were also measured, and parts of their trajectories are shown in Figure 6. Points 5-12 belong to one bright band which appeared as the most noticeable wave of III-b type. The points moved within a range of heights of 80-84 km, but we can never consider that the vertical oscillations of the measured III-b wave were limited to these heights. Obviously, only the visible part of the wave surface is being measured here. The other parts of the wave were either concealed or too transparent, and were not identified. Without a simultaneous analysis with time-lapse photography, the researchers are forced (by necessity) to make incomplete measurements. It is probable that only one end of the III-b was in a convenient position (in relation to the observer), and that the measurements (Points 13 and 14) showed a broader range of heights, i.e., from 81.1 to 86.2 km. At the moment when the measurements were begun, Point 13 was rising, but it began to drop after 2 min; after 3 min, it had dropped to $\approx$ 81 km. It is possible that this point described /16 the crest of the III-b wave, if the measurements were related to the same segment of the wave surface. Point 14 moved downward at a very high velocity (28 m/sec) for 3 min; during this time, it dropped almost to 6 km. This is close to the entire amplitude of the phase oscillation for a wave of III-b type. The authors of the measurements in [35] considered that the error in determining the velocity did not exceed ± 1 km, and that those in determining the velocity did not exceed ± 10 m/sec.

However, these values of the heights cannot determine the entire amplitude of the wave, since certain elements of its surface could be concealed from

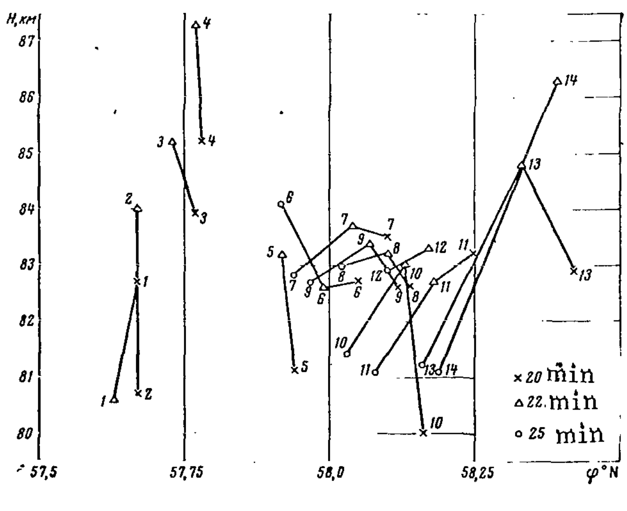


Fig. 6. Heights of Individual Points in Noctilucent Clouds Observed in Latvia on the Night of June 30 - July 1, 1961.

TABLE 2

| No. (in sequence) | No. Pair & Point | Horiz. Velocity, m/sec | Vert. Velocity, m/sec | Angle of Inclination, degrees |
|---|---|---|---|---|
| 1 | I—II 1 | 72 | —17 | —13,5 |
| 2 | 2 | 59 | +28 | +25,5 |
| 3 | 3 | 32 | +11 | +19,0 |
| 4 | 4 | 31 | +17 | +29,0 |
| 5 | 5 | 70 | +18 | +14,5 |
| 6 | 6 | 66 | — 1 | — 1,0 |
| 7 | 7 | 62 | + 1 | + 1,0 |
| 8 | 8 | 62 | + 5 | + 4,5 |
| 9 | 9 | 65 | + 6 | + 5,0 |
| 10 | 10 | 85 | +24 | +16,0 |
| 11 | 11 | 66 | — 4 | — 3,5 |
| 12 | 13 | 92 | +15 | + 9,5 |
| 13 | II—III 6 | 73 | + 8 | + 6,0 |
| 14 | 7 | 70 | — 5 | — 4,0 |
| 15 | 8 | 55 | — 1 | — 1,0 |
| 16 | 9 | 69 | — 4 | — 3,5 |
| 17 | 10 | 60 | — 9 | — 8,5 |
| 18 | 11 | 60 | — 9 | — 8,5 |
| 19 | 12 | 58 | — 2 | — 2,0 |
| 20 | 13 | 110 | —20 | —10,5 |
| 21 | 14 | 44 | —28 | —32,5 |

the observer; moreover, measures evidently were not taken to ensure complete measurement of the entire wave contour. Thus, these extremely interesting factual materials still do not answer certain important questions. Among these questions is the particularly important one concerning the entire range of heights occupied by the phase oscillations of the cloud layer. We also cannot agree with the authors in regard to their interpretation of the results of the measurements as data which supposedly confirmed the phenomenon of "strong turbulent movements in the mesopause". The authors themselves maintained [35] that they measured the morphological formations of III-a and III-b waves. If this is so, then a partial characteristic of an ordered wave movement of a layer of noctilucent clouds of the III-a and III-b types is given in [35]. This process cannot be related to the phenomena of turbulence. Naturally, there are turbulent movements in the mesopause, but their external appearance in a morphological structure is indicated only by the blurred appearance of the contours of the cloud shapes. The convective movements have their characteristic markings, and do not differ substantially from wave formations.

The results of measurements of the heights of individual points in the field of noctilucent clouds observed on the morning of August 2, 1964 are given in a work by M.I. Burov [36]. Of the nine pairs of photographs measured, one pair is presented in the article. The measured points are not marked in the photographs, and there are no indications in the text of the types of morphological forms for

which the heights were measured. Judging by the photographs, wave forms of III-b type predominated in the measured noctilucent clouds; it is possible that there were also examples of the III-c type. The front of the III-b waves is almost precisely perpendicular to the line of sight from the point of observation. The measured heights are within the range from 73.4 to 94 km (Fig. 7). The maximum density of the points is within the height range of 78-90 km. Obviously, the noctilucent clouds did not occupy this entire 20-kilometer layer of solid mass. Judging by the photographs in [36], the real thickness of the cloud layer could be within the limits of 1-2 km. Thus the scatter of the measured points by heights is due to the wave curvature of the cloud layer. In this case, it was not the entire wave surface (from the peak to the bottom) which was being measured, but some unknown (to us) part of it. Table 3 gives the horizontal and vertical velocities of certain points shown in Figure 7, as well as the angles of inclination of the cloud surface /17
along which these points moved. In all probability, these velocities are those for the brightest combined points of different types of wave oscillations (as in [35]).

The temperature conditions for cloud formation in the mesosphere are examined according to the factual observational data. The wave processes periodically raise and lower a certain section of the layer of noctilucent clouds. According to the measurements in [35], the III-a and III-b waves had total vertical oscillations within a height range of 80-87 km or (if we add the sections of the waves which were not measured) a range of 78-90 km according to [36]. According to the data for a standard atmosphere (All-Union State Standard 4401-64), the curve for the temperature at these altitudes is almost isothermal: at $H$ = 78 km, $T$ = 191.8° K; at $H$ = 80-90 km, $T$ = 185° K. The real temperatures in the mesopause at the moment and site of the appearance of noctilucent clouds reached 130° K during the measurements of the American-Swedish experiments in 1962; this value is 55° K less than the standard /18
values for a layer at 80-90 km. This means that the mesopause had very low temperatures during these cloud formations. By analogy with the standard atmosphere, we can find that the vertical length of a particularly

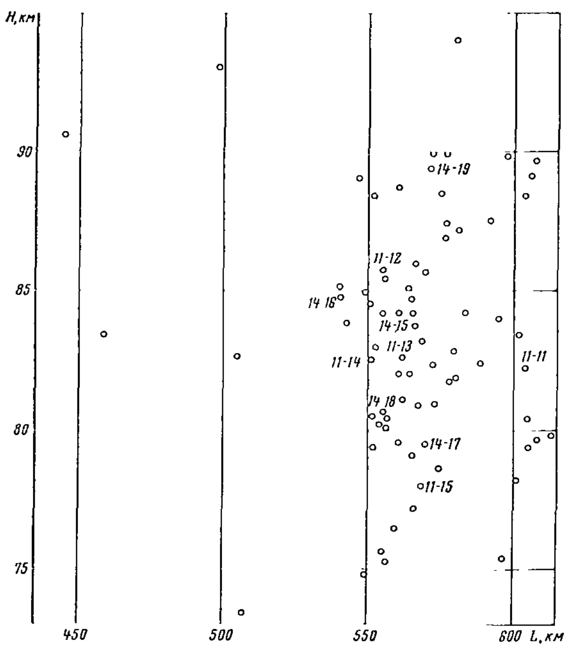


Fig. 7. Heights of Individual Points in Noctilucent Clouds Observed in Estonia on August 1-2, 1964.

TABLE 3

| No. (in sequence) | No. Point | Velocity | | Angle of Inclination, degrees |
|---|---|---|---|---|
| | | Horizontal, m/sec | Vertical, m/sec | |
| 1 | 11—11 | 29 | + 9 | +17 |
| 2 | 11—12 | 35 | +10 | +15 |
| 3 | 11—13 | 18 | + 2 | + 5,5 |
| 4 | 11—14 | 59 | —10 | — 9,5 |
| 5 | 11—15 | 26 | —13 | —26,5 |
| 6 | 14—15 | 41 | — 6 | — 8,5 |
| 7 | 14—16 | 93 | 0 | 0 |
| 8 | 14—17 | 122 | +10 | + 4,5 |
| 9 | 14—18 | 95 | —11 | — 6,5 |
| 10 | 14—19 | 35 | +12 | +19 |

cool layer is about 10 km. Thus, we can assume that the wave oscillations in a cloud layer with III-a and III-b waves occur in a range of heights which have a low temperature gradient. This circumstance can explain the lack of substantial changes in the real density and thickness of a cloud layer in various sections of a wave surface which contains III-a and III-b types. These waves are internal gravitational formations, the theory of which is only beginning to be developed [37].

The extremely long waves of III-c type play an important part in the activity of noctilucent clouds. Their length varies from 50 to 200-300 km, and perhaps more. We have observed such waves many times, [38] and have recorded them by normal photography and time-lapse photography. Figure 8 shows an example of such a wave; it was observed in noctilucent clouds on July 6-7, 1951. On the crest of very long III-c waves, there can be a cloud field with an area of many hundreds of thousands of square kilometers. It is much more difficult to detect III-c waves from the normal distance. We determined the amplitude of oscillations of III-c waves only by a morphological analysis of photographs which were obtained from one site. According to these data, the amplitude can have values of 20-30 km. We still have not undertaken special photogrammetric measurements of the height contour of III-c waves. However, the data in [36] may pertain, in part, to III-c waves (see Fig. 7). For example, if a III-c wave takes up a range of heights from 70 to 95 km, then the temperature of the medium changes (according to the standard atmosphere of the All-Union State Standard 4401-64) from 219.1° to 185° K, i.e., the difference in the temperatures for the crest and trough of the wave is about 34° K. If we take the temperature of 130° K measured in a layer of noctilucent clouds as a minimum, then the difference can reach 89° K. Under actual conditions for the appearance of noctilucent clouds, such a temperature drop is sufficient for a substantial change in the local aerological /19

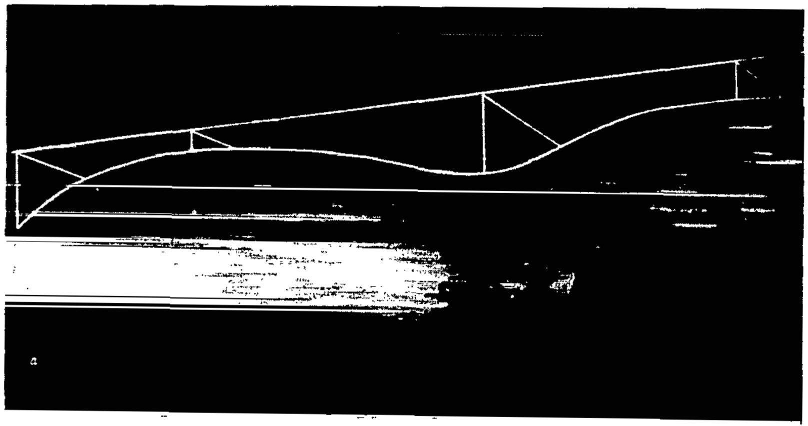

Fig. 8a. Photograph of the Western Edge of Noctilucent Clouds Observed on July 6-7, 1951. The White Lines were Plotted for a Qualitative Indication of the Wave Profile in the Cloud Field.

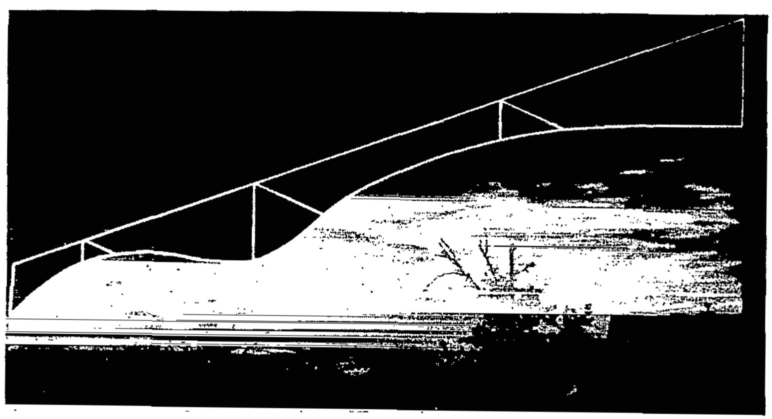

Fig. 8b. Photograph of the Western Edge of Noctilucent Clouds Observed on July 6-7, 1951. Photograph b was Made 66 min After Photograph a. The White Lines were Plotted for a Qualitative Indication of the Wave Profile in the Cloud Field.

conditions for cloud formations, all other conditions being equal. The section of the field of noctilucent clouds measured by M.I. Burov was (possibly) located in one of the III-c wave elements. According to the data of the morphological analysis of the photographs shown in [36], this assumption can be made with a certain degree of probability. This might aid in explaining the measurements of the height ranges from 73 to 94 km. Actually, the disappearance of the left-hand edge of noctilucent clouds [36] is similar to their disintegration during a change in the properties of the medium, in the same way that the appearance of the noctilucent clouds shown in Figure 8 changes. The profiles of III-c waves are marked qualitatively by the contour lines in the two photographs. During the interval between the two photographs, the crest of the III-c wave shifted to the northwest at a rate of 45 m/sec. We can clearly see that the noctilucent clouds disappear almost completely at the trough of the wave.

We have discussed the mechanisms for excitation of III-c waves in other studies [34, 39]. The ideas examined there have now been substantiated by new studies. Our comparison of an anticyclone to a moving mountain, causing large-scale gravitational waves which are transformed in the mesosphere and affect the thermodynamic conditions for cloud formations there, is now on a firmer foundation. The kinetic energy of a powerful anticyclone is sufficiently great to excite a wave oscillation of the overlying rarefied layers of the atmosphere [40]. The experimental discovery of a migration of gravitational waves of a planetary scale from the troposphere to the mesosphere will probably necessitate special methods for an aerosynoptic sounding of the atmosphere.

## The Stratification of Noctilucent Clouds

The noctilucent clouds which appeared on June 20-21, 1950 were exceptionally bright. The wave shapes formed in a dense cloud layer were covered in places with a rather thick, flocculent veil. At local midnight, the center of the Sun was below the horizon by $-h_{\odot} = 10.9°$. The density of the veil was so great at some points that it completely obscured the crests of the cloud waves behind it. The brightness of the veil increased significantly toward morning ($-h_{\odot} = 9°$). Subsequently, having analyzed the photographs, we drew /20
the conclusion that the veil of the noctilucent clouds was lower than the wave forms. The following year was particularly rich in bright clouds. On the night of July 10 to 11, 1951, there again appeared very bright clouds with a very noticeable veil. As usual, the brightness of the veil increased toward morning. This time, the veil layer underwent wave oscillations of types III-a and III-b. Figure 9 shows a photograph of these clouds for $-h_{\odot} = 9.5°$. We can clearly see the breaks (openings) in the veil layer, through which the wave structure of the overlying layer is visible. When we used time-lapse photography, it was much easier to find the two layers, and this was seen more often. We found that each layer moved in a different direction. For example, the upper layer of the clouds

observed on July 15-16, 1958 had a wave movement toward the west, while the lower cirriform, flocculent layer of the veil moved toward the east. This phenomenon is seen very clearly on a motion-picture screen, and its outward appearance resembles the movement of various levels of tropospheric clouds.

It follows from our data that the layer of the veil, or individual bunches of it, can be best observed against the background of the upper layer of the noctilucent clouds when they are 10-15° below the horizon and the position of the Sun below the horizon is not lower than $-h_{\odot}$ = 11-12°. The conditions for observing the veil at $-h_{\odot}$ = 9-8° are greatly improved. Obviously, the lower layer, or the veil of the noctilucent clouds, is in the shade during astronomical twilight and cannot be observed. As the angle of solar depression decreases, the Earth's shadow sinks correspondingly lower; thus, lower altitudes of the atmosphere are illuminated. At the beginning, only the upper layer of the veil is illuminated for $-h$ = 10-11°. Subsequently, only its upper, "smoking", haze-like streams are visible. When $-h_{\odot}$ = 9-7°, the entire layer of the veil is illuminated. Its brightness increases rapidly and sometimes exceeds the brightness of the upper layer of clouds. A rather

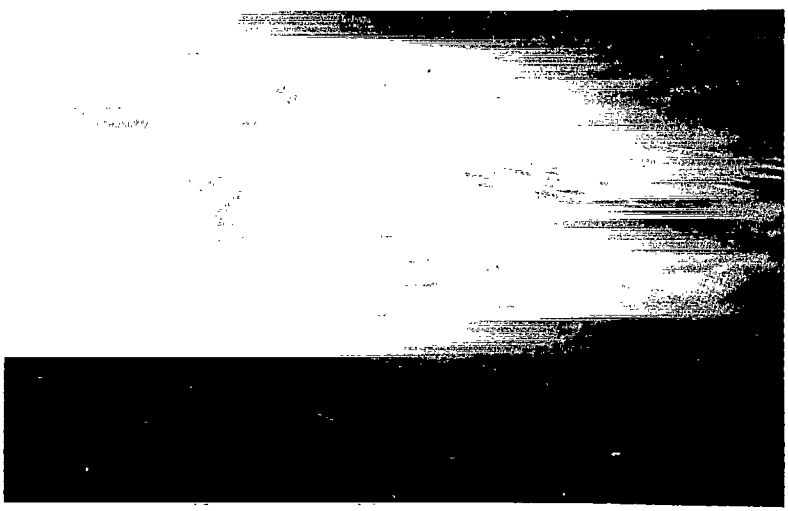

Fig. 9. Part of the Field of Noctilucent Clouds Observed on July 10-11, 1951. The Photograph was Rotated 180°. A Thick Veil Covers the Wave Layer of Noctilucent Clouds Almost Entirely.

rapid, distinctive "influx" of a new cloud picture is observed. A thin layer which has just been observed disappears and is replaced by the hazy picture of the layer of the veil of noctilucent clouds. Its morphological structure is occasionally distinguished by its complexity, but the more indistinct contours predominate. This can be explained by the shorter distance of the veil sections from the observer.

In addition to the fog-like flocculent shroud, wave curvatures of the layer (obviously, of all three types of waves) can appear in the veil, as well as crescent-shaped nuclei, "whitecaps" and round openings (which are found particularly frequently); the latter formations are of a clearly convective nature. The linear thickness of the veil layer is greater than that of the upper cloud layer, in our opinion, and can reach 5-10 km. The veil is not always observed; it is possible that it does not always exist as a cloud layer. Precise determinations of the heights of the upper and lower levels of noctilucent clouds, as well as simultaneous aero- /21
logical sounding of the atmosphere, would be necessary to determine the validity of this idea. Under real conditions, various evolutions of the height of each layer are possible, as are their local blendings.

The two-layered character of noctilucent clouds poses new questions; without an answer to them, we can never understand the physical nature of these clouds correctly. We still do not know if the veil moves with the wind or as the result of a phase oscillation of atmospheric waves which produce advantageous conditions for its formation. What is the role of the cellular turbulence in the evolution of the veil? What is the role of the veil in the "feeding" of the process of cloud formation in the upper layer of noctilucent clouds? The mechanism for the dynamic interaction between each of the two cloud levels is also interesting. In the clouds observed on July 10-11, 1951, the waves of the veil and of the upper layer were exactly parallel to one another.

The theoretical examination of the two-layer phenomenon of the clouds in the mesopause made by N.I. Novozhilov is particularly noteworthy. According to his first article on this problem [41], two or more temperature minima can sometimes be formed in the region of the mesopause. In the case of a simple structure of the mesopause, with one temperature minimum, there should be no internal wave movements of the atmosphere of the III-a and III-b types (according to N.I. Novozhilov). In this case, the noctilucent clouds consist of a veil and blurred bands. Novozhilov's hypothesis conforms well with the observations. We now need direct experiments, with measurements of the temperature conducted almost continuously, and further theoretical studies in this direction. Novozhilov's work is exceptionally important for the problem of noctilucent clouds and for a correct understanding of the physical nature of the mesosphere. Moreover, the factor of stability in the height of the mesopause with a temperature minimum is of particular significance. Measurements and morphological studies show that this cool layer (or two layers) undergoes significant oscillations in height. Noctilucent clouds are connected genetically to a low temperature of the medium; at the same time, however, they appear in a height range from 60-65 to 95-105 km. Due to the effect of III-c waves, a cloud field can be sloped so that the heights of various sections can differ by 10-20 km. This means that the cool layer of the mesopause can undergo periodic and significant changes in height (at least when noctilucent clouds are present).

## Edge of the Field of Noctilucent Clouds

The geometric contours of the field of noctilucent clouds are /22 of particular significance in morphology. Knowing the shape and geographic distribution of the boundaries of the cloud field, we can conduct an aerosynoptic analysis of the atmosphere and have a better understanding of the nature of the phenomenon. The complications in these studies lie in the fact that the morphology of noctilucent clouds is the external appearance of aerological processes in the mesosphere, which also have not been examined in detail. Therefore, there are many difficulties in understanding the idea of an "edge" of the field of noctilucent clouds. The gigantic III-c waves can carry such large cloud fields on the elements of their surface (in accordance with their dimensions) that a terrestrial observer will notice only part of them during one night. In Figure 8, we saw two wave crests, between which (in the trough) the clouds almost disappeared (but not entirely). There have been cases when the clouds in troughs of III-c waves have disappeared completely. In such cases, there is something which seems to be the edge of the cloud field in the trough of the wave. If we can see a second wave crest, simultaneously or shortly after, then we know that this was not a real edge, but only a local disappearance of the clouds as a result of unfavorable local conditions for their existence (for example, heating of the medium when the wave descends into the trough). A stationary terrestrial observer has a passive role. Too little information on the problem in question has been accumulated. Our concepts could change radically if the observer became an active experimentor on board a moving laboratory (for example, on board a high-altitude aircraft, a satellite, etc.) [31]. In the meantime, only the results of terrestrial observations are avilable. Figure 10 shows photographs of four moments in the development of the eastern edge of a field of noctilucent clouds observed on July 6-7, 1951. In Figure 8, we have already seen how rapidly the crests of III-c clouds shifted toward the northwest during the course of this night. On the other hand, the boundary markings at the eastern edge were relatively stable for 50 min. Subsequently, there was only a slow migration and b bending of the boundary toward the southeast. The boundary was marked by a bright band, which was the crest of an extended III-b wave. Even the very mobile III-b waves and other formations did not go beyond this boundary. This type of picture was also noted in other appearances of clouds. The boundary could tend toward the south or any other direction. It was always a clear boundary between a region with intense cloud formations and a "forbidden" region for noctilucent clouds. Why? Why do a number of ordered zones in the atmosphere preserve different properties for a long time? It is possible that this is part of a global wave which is rather steep at this site, and which has a high temperature gradient. All this is still very unclear. This is another reason why mobile /23 high-altitude measurements and aerological soundings of the mesosphere are necessary.

The geographic boundaries for the possible propagation of noctilucent clouds are closely connected with the problem in question.

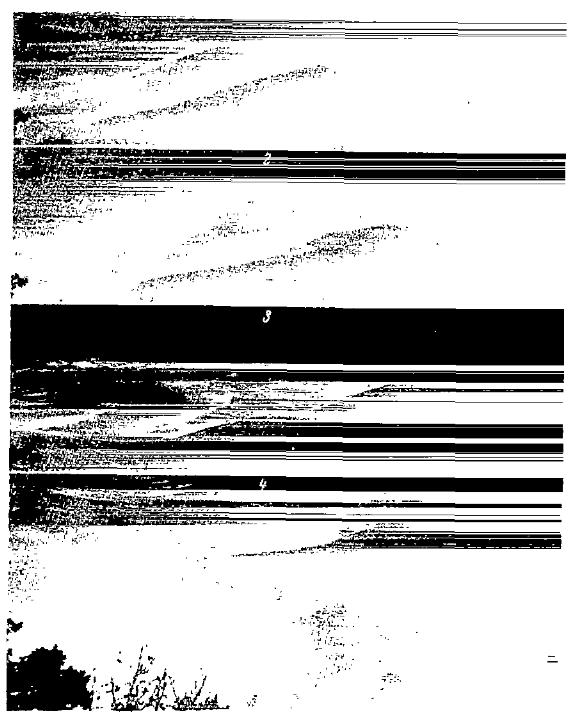

Fig. 10. Four Successive Photographs of the Eastern Edge of the Noctilucent Clouds of July 6-7, 1951.

It is usually considered that the zone for a possible appearance of noctilucent clouds is limited to a latitude belt of 50-70° for the Northern Hemisphere and a similar belt for the Southern Hemisphere. However, an analysis of the observational data obtained during the entire period during which noctilucent clouds have been studied indicates a very reliable circumstance of a slightly different nature. It is very possible that the "permissible" zone for noctilucent clouds is not a latitude belt but a polar cap. The concept of the edge of this noctilucent, or azure-blue, "cap" of the Earth can change. It is possible that there is a small local zone which has no clouds at the center of this "cap"; this zone could be determined by the structure of mesospheric or planetary circulation.

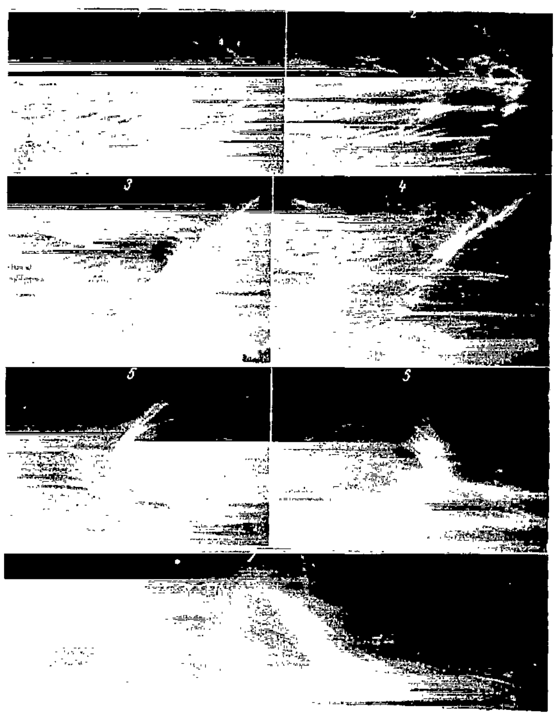

Fig. 11. Seven Subsequent Photographs of a Section of Convective Disturbance in the Noctilucent Clouds of July 6-7, 1951.

Global methods for studying the atmosphere are also necessary for a final solution to this problem.

## Convection in Noctilucent Clouds

The convective processes in the mesosphere are revealed by the characteristic morphological shapes of noctilucent clouds. The thermobaric nature and scale of their development in the mesosphere have still been studied insufficiently. We do not know the nature of their role in the formation and development of noctilucent clouds. There are very few factual observational data concerning this problem; there are many methodological difficulties in interpreting the observations.

Noctilucent clouds have shapes which resemble eddies or cellular convection in their outward appearance. They represent dark, round "holes" in a cloud layer. They are classified morphologically as Type IV [4]. Time-lapse photography has recorded several cases of local sections in clouds which are trapped by an eddy. We know of several cases of large-scale eddies. V.A. Bronshten and G.O. Zateyshchikov conducted measurements for one such eddy [42].

Let us examine a series of photographs of a segment of a cloud field which was agitated by a convective motion and observed on July 6-7, 1951. Figure 11 shows several of these photographs (not inverted). Each photograph corresponds to an angle of roughly 7° in the sky profile along the vertical. The disturbance traveled upward in the photograph, i.e. almost exactly toward the south, with a slight inclination toward the west.

Photograph 1 (00 min conventional time) corresponds to the beginning of the phenomenon ($-h_{\odot} = 11.6°$). In the upper right-hand corner, we can see several weak-colored bands which are arranged in /24
the cloud layer in a way that differs from the other details.

The two parallel and two converging bands still have not shown any particular activity.

Photograph 2 (21 min conventional time) shows a significant increase in the brightness and a powerful dynamic activity in the disturbed section of the clouds. The cloud waves go from the base of the distinct eddy to the sides. The brightest parts of the disturbance are lagging somewhat and not participating completely in the wave oscillations of the layer.

Photograph 3 (23.5 min conventional time) and Photograph 4 (28 min conventional time) illustrate a rapid development of the disturbance. A concentrated current of cloud matter is spreading from the right to the left and down (in the image in the photograph). Half of the current (roughly from the middle) is in contact with the cloud layer. The cloud mass seems to flow from the sides of the current, and moves into the wave field. In the upper right-hand corner of the photograph, part of the current is hazed over with cloud streams and moves from the general cloud level downward, toward the Earth. The bright, central part of the current is not affected by the wave oscillations of the field. It is adjacent to the wave field at the bottom. Thus, an almost linear movement of the cloud mass downward, at a certain sharp angle to the wave layer of the clouds, is observed in Photographs 3 and 4.

Photograph 5 (49 min conventional time) was obtained for $-h_{\odot} = 11.3°$. The end of the current which is toward the Earth's surface branches out toward the hazy cloud streams. The upper end of the current (it is below the center in the photograph) is resting on the cloud field. The current has curved somewhat, but it is still maintaining the previous direction from right to left (for the image in the photograph).

Photograph 6 (56.5 min conventional time), for $-h_{\odot} = 11°$, shows a digression of the current. Its direction is now from the left to the right. The current is shorter but much wider. At its origin, we can see multiple individual streams which merge with the dense bright current. Its upper end (the lower end on the photograph) is connected to the cloud field and seems to supply it with cloud matter. The current is very hazy and less clearly outlined.

Photograph 7 (67 min conventional time). The Sun had begun to rise more rapidly; $-h_{\odot} = 10.7°$. The current is illuminated by the Sun more fully. Its upper end is still in contact with the cloud field (at the bottom of the photograph). The lower end is not broken off now, but is clearly joined to the hazy mass of the veil. This second lower cloud layer did not develop greatly in area, or had not been completely illuminated by the Sun. Only a small foggy coagulation is noticeable; the current originates in this coagulation. The current tends to flow upward and join the principal, upper layer of noctilucent clouds.

Unfortunately, we were not using time-lapse photography in 1959; the materials would have been much more complete if we had /25
used it. It could have determined the direction of the migration of the cloud mass inside the current, and other details of this interesting phenomenon, unequivocally. In this section, we have been giving the direction of the current according to a general morphological analysis.

## Nature of Noctilucent Clouds

Morphological studies give objective information concerning the space-time evolution of the geometric coordinates, dimensions, and parameters for the movement of various sections of noctilucent clouds. These factual data are the basis of a study of the physical and chemical nature of the phenomenon. This study concerns the aerological conditions for the formation and chemical composition of noctilucent clouds. The mesosphere and the troposphere have a certain similarity and, at the same time, a number of principal differences. There is a complex of physical and chemical phenomena which exists in each sphere and only in this sphere. For a correct examination of the processes developing there, we should always keep this circumstance in mind.

The possibility that noctilucent clouds are formed by a condensation of water vapor in the upper mesosphere has been examined in several theoretical works [5, 43, 44]. The American-Swedish rocket experiments of 1962 have confirmed the fact of a condensation process in the zone of noctilucent clouds. The cloud particles were found to have a roughly spherical shape. The condensed substance evaporated rapidly, leaving round traces on the special surface of a sampler. Solid particles which also had a spherical shape were found at the center of these cloud particles. The solid particles, which played the role of condensation nuclei, appeared to be products of the volatilization of meteoroids in the upper layers of the atmosphere. This was confirmed by an analysis of their chemical composition [45]. According to the reaction with the calcium surface of the sampler, the authors of this experiment considered that the condensed part of the cloud particles consisted of water. The first direct experiment should encourage more objective analysis of broader information in the future. In subsequent experiments, it will be necessary to make a more detailed chemical analysis of the cloud particles. This need results from the following circumstances. There are a number of basic difficulties in understanding the physical and chemical process of the formation of noctilucent clouds from water vapor. One of the principal factors is solar radiation, with a wavelength from 1750 to 2400 Å, penetrating almost to 60 km; this causes photodissociation of $H_2O$. This problem is examined in /26
detail in an article in this collection written by I.A. Khvostikov, and also in [44, 46, 47]. By different types of dissociation, the $H_2O$ molecules can disintegrate in the following reactions:

$$H_2O + h\nu \rightarrow OH + H;$$
$$H_2O + h\nu \rightarrow H_2 + O;$$
$$H_2O + h\nu \rightarrow 2H + O;$$
$$H_2O + O_2 \rightarrow HO_2 + O \text{ and further:}$$
$$HO_2 + O \rightarrow OH + O_2.$$

The discrete absorption section of $H_2O$ for the entire ultraviolet spectral region give a significant value. For example, during laboratory spectrophotometrical analysis, irradiation of a definite volume of air can cause abrupt and rapid photochemical changes in the vacuum ultraviolet region. In order to obtain stable and reliable results, the gas being analyzed is blown through a gap between the working openings of the analyzer during the time of the analysis [48].

In the mesosphere at high latitudes, the processes of photodissociation act continuously during the entire summer period. From May to August (i.e., during the period when noctilucent clouds appear most frequently), the Sun practically does not go beyond the horizon in the upper half of the mesosphere. The recombination reactions are effective during the night hours, i.e., when there is no dissociating solar radiation. All this causes great difficulty in understanding the process of accumulation of $H_2O$ molecules and their subsequent condensation in noctilucent clouds.

It is obvious that water vapor can be "at rest" only when it is below 30 km, i.e., below the shielded ozone layer which absorbs solar radiations with wavelengths shorter than 2950 Å.

Therefore, I.A. Khvostikov [44] and other authors [39, 49-51] have examined various working hypotheses on the transfer of water vapor into the mesosphere or its formation in the immediate vicinity of the noctilucent clouds, if only at the time of their appearance. It is possible that the sporadic cases when noctilucent clouds were formed from water vapor were the result of a coincidence of advantageous conditions which allowed the water vapor to exist for a certain time under equilibrium conditions in the upper part of the mesosphere. However, we are still not completely sure of this problem. Therefore, further research studies, both experimental and theoretical, are quite necessary.

In relation to this, the American rocket experiments with spraying large quantities of water at altitudes of 100-150 km (86 tons) and 90 km (95 tons) are particularly interesting. These /27 incidental experiments showed an almost instantaneous disappearance of the large masses of water in the mesosphere. The enormous local supersaturation of water vapor did not cause even a temporary cloud formation. There can be two explanations for this: either the temperature of the mesosphere over Cape Kennedy was too high on October 27, 1961 and April 25, 1962 and the saturation pressure of the water vapor was not sufficient for its condensation [52], or, during the process of the spraying, the water vapor rapidly ceased to be affected by the processes of photodissociation and dissociated into simpler gas molecules and atoms. This type of experiment should be repeated in a region where noctilucent clouds actually are present. It is very possible that there is another substance (other than $H_2O$) in a vapor state in the mesosphere which condenses at times into a thin layer of blue clouds.

Another factor which does not completely conform with the observations is the chromaticity of noctilucent clouds. Clouds which consist of water vapor have a white color. Nacreous clouds, which consist of ice crystals, display all the colors of the rainbow during illumination by the Sun. Noctilucent clouds never become irridescent; they have an azure-blue tint. Only when noctilucent clouds are in the vicinity of the horizon and affected by the lower layers of the troposphere do they sometimes seem (to the terrestrial observer) to acquire a light whitish or yellowish shade. Noctilucent clouds are persistently azure-blue where the interferences of the dust-filled atmosphere are insignificant (for example, in the region around the zenith). The chromaticity of noctilucent clouds depends on their composition and on the dimensions of the cloud particles. High cirrus and, in particular, nacreous clouds resemble noctilucent clouds in the dimensions of the cloud particles, but they are never persistently azure-blue. This means that azure-blue vapors of some substance other than $H_2O$ take part in the process of condensation. Moreover, the condensed substance does not convert into a solid, crystal state, but remains in a vapor state. The water sprayed at altitudes of 90-150 km over Cape Kennedy in 1961 and 1962 was almost instantaneously converted into a white globular cluster of ice crystals which disappeared without a trace within 10-12 sec (see above).

The properties mentioned above (as well as others not mentioned) are still inexplicable and require more attentive examinations on the part of the observers. In relation to this, it seems expedient to examine a rather different, but probable, model for the formation of noctilucent clouds. The basis for this model is oxygen - the most abundant element on earth. In a free or chemically bound state, oxygen constitutes almost half the mass of the Earth. It makes up about 86% of the mass of the ocean water. In the atmosphere, gaseous oxygen constitutes roughly 23% of the mass and 21% of the volume of dry air. The hydrometeorological processes of the atmosphere extending to an altitude of 100-120 km are due to various /28 chemical and physical occurrences of oxygen.

Liquid hydrogen oxide (liquid $H_2O$) forms the oceans, seas, and rivers. They absorb incident short-wave radiation and convert it to thermal radiation. Together with the vapor phase of $H_2O$, the hydrosphere and atmosphere form the thermal regime of the troposphere. In the troposphere, a large quantity of different types of vaporized $H_2O$ clouds, as well as the moisture content which did not form clouds, participate actively in the radiation exchange of the atmosphere. The highest $H_2O$ clouds are the nacreous ones. They are formed under certain conditions over the mountain regions of Norway and Canada, primarily during the winter months. Moist air flows around mountain peaks to altitudes of 25-29 km, and the lenticular "lenses" of nacreous clouds are formed at the crests of the air waves. The most detailed studies of this type of cloud were made by C. Störmer in Norway. Above 25-29 km, the concentration of $H_2O$ vapor rapidly decreases because of photodissociation (which becomes more effective as the altitude is increased). Thus, the thermodynamic properties of the troposphere are largely determined by the work of liquid and vaporized water.

In the mesosphere, oxygen oxide ($O_3$) has the task of absorbing ultraviolet radiation (shorter than 3000 Å) and heat transfer.

Thus, the region with the maximum $O_3$ content for radiation shorter than 3000 Å is the absorbing layer. The structure of this layer is not uniform. As in the hydrosphere, the temperature increases with altitude (within an interval of 30-50 km) and it reaches a maximum in the region of 50-55 km [53].

The flocculent structure of the ozonosphere produces a complex system of meso-scale convective and turbulent motions of the atmosphere. The most powerful ones rise upward to the height of noctilucent clouds, forming certain morphological shapes in the cloud layer. At altitudes higher than 50 km, there is apparently a mechanism for radiational cooling of the atmosphere; a deep temperature minimum is found in the mesopause as a result of this cooling.

Throughout the entire mesosphere, to an altitude of 100-120 km, the oxygen is mainly in a molecular state. It is expedient that we examine more closely the possibilities for a conversion from gaseous oxygen or polymeric oxygen compounds ($O_3$, $O_4$, etc.) to a vapor phase which can form clouds like the noctilucent ones. The absorption spectrum of liquid oxygen is given in Figure 12 according to the data in [54]. Three curves for the spectral distribution of the light intensity of noctilucent clouds are plotted in relative units in this figure [55]. The spectra were obtained in 1951 with the aid of a single-prism spectrograph. The dispersion was extremely low and changed from 300 Å for 1 mm in the blue to 3000 Å for 1 mm in the red part of the spectrum. The length of the photographic image of the spectrum was 2.7 mm in the negative. The /29

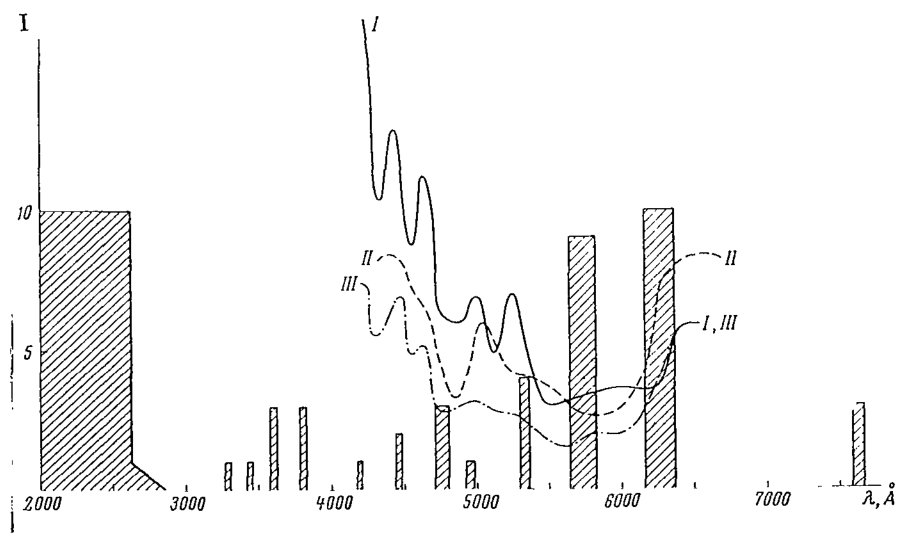


Fig. 12. Curves of the Spectral Distribution of the Intensity (in Relative Units) of Noctilucent Clouds, and the Schematic Diagram of the Liquid Oxygen Absorption Bands (Lines). (I) June 22-23; (II) July 6-7; (III) Average Curve for Three Dates in 1951 when Noctilucent Clouds Appeared.

relative distribution of the spectral segments was determined by the scale of the recording microphotometer (1:400). The possible error in determining the wavelength could reach ± 300 Å in the red and ± 50 Å in the blue. Unfortunately, we do not have any information on how to examine the spectrum of noctilucent clouds with a higher resolution. Therefore, it is very possible that there are such errors in the position of the maxima and minima in the spectral distribution.

A qualitative analysis of these curves for the oxygen absorption bands shows that there are certain rules for their arrangement. The two high-capacity liquid oxygen bands ($\Delta\lambda_4$ = 5640 - 5826 Å and $\Delta\lambda_5$ = 6160 - 6368 Å) coincide almost exactly, with a deep minimum in the spectral distribution of the primarily reflected light of the noctilucent clouds. On the other hand, there is an abrupt increase in the light intensity of the noctilucent clouds in the region of rare and rather weak $O_2$ absorption bands. We can see that there is a coincidence (although a less reliable one) between the weak absorption bands ($\Delta\lambda_1$ = 4180 - 4208 Å, $\Delta\lambda_2$ = 4456 - 4481 Å, and $\Delta\lambda_3$ = 4710 - 4802 Å) and the corresponding small minima (which are not always very clear) in the spectral distribution of the light of noctilucent clouds. It follows from Figure 12 and the data in /30
the references that liquid oxygen has a pale blue color which closely resembles the color of noctilucent clouds. We consider this agreement between the spectrum of noctilucent clouds and that of liquid oxygen very significant. In relation to this, it is extremely important that special studies be conducted to investigate the conditions for the formation of oxygen vapor (or that of its polymers) and its condensation or agglomeration as applied to a complex of physical and chemical processes prevailing in the mesosphere. The existing thermophysical characteristics of the phase states of oxygen were based on experimental data obtained in laboratories with pressures from many atmospheres to 1 mm Hg [56]. The conditions of a free atmosphere, low pressure (from 0.01 to 0.001 mm Hg0, the electrostatic forces of the condensation nuclei, and many other factors were not considered in these experiments. Moreover the properties of oxygen polymers have been studied only in isolated articles. The paramagnetic properties of liquid oxygen could play an important part in the process of its condensation or the agglomeration of individual primary clusters of molecules in charged particles formed by the evaporation of meteors.

We should keep in mind that there is much in the theory of condensation itself that is still unclear when the conditions of the process differ substantially from the regular moist atmosphere [57].

There is a powerful thermodynamic mechanism which acts in the mesosphere, at least during the period when noctilucent clouds exist. As we have shown above, the wave oscillations and convective currents rapidly raise and lower large volumes of air. The conditions are set for its periodic cooling, roughly by 100° K.

Multiple repetitions of this process during a relatively short time interval can cause accumulation of primary amalgamations of oxygen (or its polymers) molecules. Their condensation or agglomeration around the condensation nuclei begins in the region with the greatest cooling. Subsequently, the cloud particles can represent relatively small gaseous (loose) accumulations of oxygen molecules (or polymers) around the condensation nuclei. This condition can be extremely unstable, and can be disrupted by evaporation as soon as the properties of the medium become disadvantageous for the wave oscillation of the atmosphere.

Subsequently, photodissociation of molecular oxygen begins to predominate at points higher than 130 km. Oxygen molecules can exist in the mesosphere for a relatively long period under the direct rays of the Sun. Moreover, it might not be $O_2$, but $O_3$ or higher oxygen polymers which take part in the formation of noctilucent clouds. This favors higher temperatures for the thermophysical properties of their vaporization. For example, the boiling temperature of $O_3$ is 71° K higher than that for $O_2$. /31

The thermophysical properties of the higher polymers have not been studied in great detail.

Obviously, there should be a close genetic connection between the process of oxygen cloud formation and the activity of elementary photochemical processes in the mesosphere. In this respect, the observations of N.N. Shefov, who discovered an increase in the intensity of OH and $O_2$ emissions during the appearance of noctilucent clouds [58], are very interesting.

A confirmation of the oxygen model for noctilucent clouds could be of important value in understanding the physics of the entire atmosphere of the Earth. In particular, it could aid in a similar explanation of the composition of Hoffmeister's luminous bands [59] which are now very puzzling (for example, those of atomic oxygen). This phenomenon has been observed and studied primarily by C. Hoffmeister in Sonneberg (Germany). The luminous bands are located at an interval of 90 - 180 km (higher than noctilucent clouds). Atomic oxygen predominates there, and the radiation conditions for the existence of any clouds there are even more rigid.

The problem of noctilucent clouds is closely related to the understanding of the physics of atmospheres of Mars and Venus. There are blue clouds and even entire violet atmospheric layers on these planets. They have been compared many times with noctilucent clouds [60]. Their chemical composition is still unclear. The lack of $H_2O$ in the Martian atmosphere excludes the possibility of their formation from water vapors. However, their cloud particles are in a liquid phase, according to polarization measurements [61]. The seasonality of their appearance (summer), the conditions for their best visibility (terminator) [62], as well as the discrimination in relation to the underlying surface [61] and their higher altitudes [60] indicate a close connection between them and noctilucent clouds. The height of the blue clouds on Mars is apparently about 100 km. There is a level of blue haze and cloud bands visible in the blue rays on Venus, although it is less clear [63]. In different models, the height of this level has been evaluated as 100 and 40 km. The figure of 100 km seems to be more plausible.

## Conclusions

(1) Morphological studies are finding important properties in /3
the physical nature of noctilucent clouds.

(2) The results of morphological studies are being used for the development of physical and chemical studies of noctilucent clouds.

(3) The condensation theory of noctilucent clouds is the most probable one.

(4) The chemical composition of the condensed material in noctilucent clouds should be studied in greater detail. In the meantime, we cannot assume that water vapor is the only possible substance comprising the condensed part of noctilucent clouds. In this regard, it is expedient that future experimental and theoretical studies take the probable compositions of noctilucent clouds into account.

## REFERENCES


1. Krinov, Ye.L.: Instruktsiya dlya nablyudeniy svetyashchikhsya oblakov (Instructions for Observations of Luminous Clouds), in: Astron. kalendar'. Peremennaya chast'na 1936 g (Astronomical Calendar. Alternate Section for 1936). Gor'kiy, 1935, pp. 174-179.
2. Zateyshchikov, G.O. and V.A. Bronshten: Instruktsiya dlya nablyudeniy serebristykh (nochnykh svetyashchikhsya) oblakov [Instructions for Observations of Noctilucent (Nocturnal Luminescent) Clouds]. Meteorologiya i Gidrologiya, No. 7, pp. 108-109, 1937; Byull. VAGO, No. 2, pp. 22-25, 1939.
3. Bronshten, V.A.: Instruktsiya dlya nablyudeniy serebristykh (nochnykh svetyashchikhsya) oblakov [Instructions for Observations of Noctilucent (Nocturnal Luminescent) Clouds]. Izdat. Akad. Nauk S.S.S.R., 1948.
4. Grishin, N.I.: O strukture serebristykh oblakov (The Structure of Noctilucent Clouds). Astron. Tsirkulyar, No. 147, pp. 20-24, 1954; Meteorologiya i Gidrologiya, Vol. 1, pp. 23-28, 1955; Byull. VAGO, No. 16 (23), pp. 3-6, 1955.
5. Khvostikov, I.A.: Serebristyye oblaka i stroyeniye stratosfery (Noctilucent Clouds and the Structure of the Stratosphere), in: Sbornik pamyati S.I. Vavilova (A Collection Dedicated to S.I. Vavilov). Izdat. Akad. Nauk S.S.S.R., 1952.

6. Chistyakov, V.F. and V.G. Teyfel': Nekotoryye voprosy prirody serebristykh oblakov (Several Problems in the Nature of Noctilucent Clouds). Byull. VAGO, No. 19 (26), pp. 17-30, 1956.
7. Grishin, N.I.: Nablyudeniya serebristykh oblakov (Observations of Noctilucent Clouds), in: Trudy vtorogo s"yezda VAGO (Works of the Second Session of the All-Union Astronomical and Geodetic Society), January 25-31, 1955. Izdat. Akad. Nauk S.S. S.R., 1960, pp. 134-136.
8. Rezolyutsiya 2-go s"yezda VAGO (Resolutions of the Second Session of the All-Union Astronomical and Geodetic Society), January 25-31, 1955. Moscow, 1955, p. 11.
9. Grishin, N.I.: Serebristyye oblaka v Tret'yem mezhdunarodnom geofizicheskom godu (1957-1958 gg) [Noctilucent Clouds during the Third International Geophysical Year (1957-1958)]. Astron. Tsirkulyar, No. 161, pp. 19-21, 1955.
10. Grishin, N.I.: O programme nablyudeniy serebristykh oblakov v Mezhdunarodnom geofizicheskom godu (1957-1958) [The Program for Observations of Noctilucent Clouds during the International Geophysical Year (1957-1958)], in: Astron. kalendar'. Peremennaya chast' na 1957 g (Astronomical Calendar. Alternate Section for 1957). Moscow, 1956, pp. 199-212.
11. Grishin, N.I.: Soveshchaniye po serebristym oblakam (A Discussion of Noctilucent Clouds). Astron. Tsirkulyar, No. 175, pp. 25-26, 1956.
12. Grishin, N.I.: Issledovaniya serebristykh oblakov (Studies of Noctilucent Clouds), in: Inform. sbornik GUGMUS (Information Manual of the Central Board of the Hydrometeorological Service). Leningrad, 1957, No. 2, pp. 16-20.
13. Programma i Instruktsiya nablyudeniy nad serebristymi oblakami na gidrometstantsiyakh vo vremya Mezhdunarodnogo geofizicheskogo goda (Program and Instructions for Observations of Noctilucent Clouds at the Hydrometeorological Stations during the International Geophysical Year), in: Inform. sbornik GUGMUS SSSR (Information Manual of the Central Board of the Hydrometeorological Service of the USSR). Leningrad, 1957, No. 2, pp. 40-43, 61-62 and 95-96.
14. Grishin, N.I.: Instruktsiya dlya nablyudeniy serebristykh oblakov (Instructions for Observations of Noctilucent Clouds). Izdat. Akad. Nauk S.S.S.R., 1957.
15. Grishin, N.I.: Nablyudatelyan serebristykh oblakov (To Observers of Noctilucent Clouds), in: Astron. kalendar Peremennaya chast' na 1958 g (Astronomical Calendar. Alternate Section for 1958). Moscow, pp. 223-236.
16. Instruktsiya dlya lyubiteley po nablyudeniyu serebristykh /33
oblakov (Instructions for Amateur Observers of Noctilucent Clouds), in: Mezhdunarodnyy geofizicheskiy god (International Geophysical Year). Sverdlovsk, "Sverdlovskiy Oblastnyy Otdel Narodnogo Obrazovaniya", 1957, pp. 13-18.
17. Semakin, N.K.: Serebristyye oblaka (Pamyatka yunym uchastnikam MGG) Noctilucent Clouds (Instructions for Young Participants of the IGY). Moscow, "Tsentral'naya Stantsiya Yunykh

Tekhnikov", 1957.
18. Martynov, D. Ya.: Nablyudayte serebristyye oblaka. Mezhdunarodnyy geofizicheskiy god. 1957-1958 (Observe Noctilucent Clouds. International Geophysical Year. 1957-1958), in: Pamyatka fiziko-tekhnicheskim, astronomicheskim i meteorologicheskim kruzhkam (Memorandum to Physico-Technical, Astronomical, and Meteorological Circles). Moscow, "Tsentral'-naya Stantsiya Yunykh Tekhnikov", 1957, pp. 11, 24.
19. Grishin, N.I.: 2-ye soveshchaniye po serebristym oblakam (Second Conference on Noctilucent Clouds). Astron. Tsirkulyar, No. 180, p. 24, 1957.
20. Grishin, N.I.: Chetvertoye soveshchaniye po serebristym oblakam (Fourther Conference on Noctilucent Clouds). Astron. Tsirkulyar, No. 204, pp. 18-20, 1959.
21. Trudy soveshchaniya po serebristym oblakam (Works of a Conference on Noctilucent Clouds), Tartu, December 12-14, 1958. Tartu, 1959.
22. Grishin, N.I.: Shestoye soveshchaniye po serebristym oblakam (Sixth Conference on Noctilucent Clouds). Astron. Tsirkulyar, No. 209, pp. 46-47, 1960.
23. Trudy VI soveshchaniya po serebristym oblakam (Works of the Sixth Conference on Noctilucent Clouds), Riga, October 22-24, 1959. Riga, Izdat. Akad. Nauk Latv. S.S.R., 1961.
24. Grishin, N.I.: Sed'moye soveshchaniye po probleme serebristykh oblakov (Seventh Conference on the Problem of Noctilucent Clouds). Astron. Tsirkulyar, No. 222, pp. 33-34, 1961.
25. Grishin, N.I.: Izucheniye serebristykh oblakov (A Study of Noctilucent Clouds). Vestnik Akad. Nauk S.S.S.R., No. 9, pp. 125-126, 1961.
26. Trudy soveshchaniya po serebristym oblakam (Works of a Conference on Noctilucent Clouds), Tallin, May 16-19, 1961. Tallin, 1962.
27. Grishin, N.I.: Samyye vysokiye oblaka (The Highest Clouds). Zemlya i Vselennaya, No. 5, pp. 73-76, 1965.
28. Meteorologicheskiye issledovaniya. Sbornik Statey, No. 12 (Meteorological Studies. A Collection of Articles, No. 12). Moscow, 1966.
29. Grishin, N.I.: Izucheniye dvizheniy serebristykh oblakov (Studying the Movements of Noctilucent Clouds). Byull. VAGO, No. 21, (28) pp. 52-60, 1958.
30. Villmann, C.I.: Nekotoryye aspekty issledovaniya serebristykh oblakov (Some Aspects of a Study of Noctilucent Clouds), in: Meteorologicheskiye issledovaniya. Sbornik statey (Meteorological Studies. A Collection of Articles), No. 12. 1966, pp. 92-100.
31. Grishin, N.I.: Morfologicheskiye issledovaniya serebristykh oblakov (Morphological Studies of Noctilucent Clouds), in: Meteorologicheskiye issledovaniya. Sbornik statey (Meteorological Studies. A Collection of Articles), No. 12. 1966, pp. 92-100.
32. Grishin, N.I.: Izucheniye dvizheniy serebristykh oblakov metodom kinos"yemki (Studying the Movements of Noctilucent

Clouds by Cinematography). Meteorologiya i Gidrologiya, No. 3, pp. 34-37, 1957.
33. Grishin, N.I.: Serebristyye oblaka v 1950-1951 gg (Noctilucent Clouds during 1950-1951). Meteorologiya i gidrologiya, No. 8, pp. 22-26, 1952.
34. Grishin, N.I.: Volnovyye dvizheniya i meteorologicheskiye usloviya poyavleniya serebristykh oblakov (Wave Movements and Meteorological Conditions for the Appearance of Noctilucent Clouds), in: Nekotoryye problemy meteorologii. Sbornik statey (Some Problems in Meteorology. Collection of Articles), No. 1. 1960, pp. 117-119.
35. Dirikis, M.A., V.S. Yevdokimenko and Yu.L. Frantsman: Opredeleniye prostranstvennykh koordinat serebristykh oblakov (Determining the Spatial Coordinates of Noctilucent Clouds), in: Meteorologicheskiye issledovaniya. Sbornik statey (Meteorological Studies. Collection of Articles), No. 12. 1966, pp. 47-51.
36. Burov, M.I.: Opredeleniye parametrov serebristykh oblakov v 1964 g (Determining the Parameters of Noctilucent Clouds in 1964), in: Meteorologicheskiye issledovaniya. Sbornik statey (Meteorological Studies. Collection of Articles), No. 12. 1966, pp. 34-46.
37. Trubnikov, B.N.: K teorii volnovykh dvizheniy v serebristykh oblakakh (The Theory of Wave Movements in Noctilucent Clouds); in this collection.
38. Grishin, N.I.: O modelirovanii stratosfernykh techeniy. Modelirovaniye yavleniy v stratosfere i gidrosfere (The Modeling of Stratospheric Currents. Modeling the Phenomena in the Stratosphere and Hydrosphere), in: Trudy Pervoy mezhduvedomstvennoy konferentsii 22-26 noyabrya 1960 g (Works of the First Joint Conference of November 22-26, 1960). Izdat. Akad. Nauk S.S.S.R., 1962, pp. 58-66.
39. Grishin, N.I.: K voprosu o meteorologicheskikh usloviyakh poyavleniya serebristykh oblakov (The Problem of the Meteorological Conditions for the Appearance of Noctilucent Clouds), in: Trudy VI soveshchaniya po serebristym oblakam (Works of the Sixth Conference on Noctilucent Clouds), Riga, October 22-24, 1959. Riga, Izdat. Akad. Nauk Latv. S.S.R., 1961, pp. 107-140.
40. Kurilova, Yu. V.: O meteorologicheskikh usloviyakh poyavleniya serebristykh oblakov (The Meteorological Conditions for the Appearance of Noctilucent Clouds), in: Meteorologicheskiye issledovaniya. Sbornik statey (Meteorological Studies. Collection of Articles), No. 12. 1966, pp. 101-105.
41. Novozhilov, N.I.: Ob uchete volnovykh dvizheniy v serebristykh oblakakh pri opredelenii struktury mezopauzy (Considering the Wave Movements in Noctilucent Clouds in Determining the Structure of the Mesopause), in: Trudy soveshchaniya po serebristym oblakam (Works of a Conference on Noctilucent Clouds), Tallin, May 16-19, 1961. Tallin, 1962, pp. 126-130. /34
42. Zateyshchikov, G.O. and V.A. Bronshten: Serebristyye oblaka v 1936 g (Noctilucent Clouds during 1936). Meteorologiya

i Gidrologiya, Nos. 11-12, pp. 3-24, 1938.
43. Khvostikov, I.A.: Serebristyye oblaka i stroyeniye atmosfery (Noctilucent Clouds and the Structure of the Atmosphere), in: Trudy soveshchaniya po serebristym oblakam (Works of a Conference on Noctilucent Clouds), Tallin, May 16-19, 1961. Tallin, 1962, pp. 7-13.
44. Khvostikov, I.A.: Priroda serebristykh oblakov i nekotoryye voprosy fotokhimii i dinamiki zemnoy atmosfery (The Nature of Noctilucent Clouds and Some Problems in the Photochemistry and Dynamics of the Earth's Atmosphere), in: Meteorologicheskiye issledovaniya. Sbornik statey (Meteorological Studies. Collection of Articles), No. 12. 1966, pp. 57-65.
45. Bronshten, V.A.: Rakety izuchayut serebristyye oblaka (Rockets are Studying Noctilucent Clouds). Priroda, Vol. 1, pp. 95-99, 1964.
46. Nicolet, M.: Aeronomiya (Aeronomy). Moscow, "Mir", 1964.
47. Krasovskiy, V.I.: Gidroksil'naya emissiya verkhney atmosfery (The Hydroxyl Emission of the Upper Atmosphere), in: Polyarnyye siyaniya i svecheniye nochnogo neba (Auroras and Airglow), No. 10. Moscow, 1963, pp. 24-34.
48. Viselov, F.I.: Spektrofotometricheskiye datchiki dlya gazoanalizatorov vozdukha na kislorod i pary vody (Spectrophotometric Units for Gas-Analyzers of the Oxygen and Water Vapor in the Air). Vestnik LGU, No. 10, pp. 40-44, 1966.
49. Villmann, C.I.: Nekotoryye soobrazheniya o proiskhozhdenii serebristykh oblakov (Some Concepts on the Origination of Noctilucent Clouds), in: Trudy soveshchaniya po serebristym oblakam (Works of a Conference on Noctilucent Clouds), Tallin, May 16-19, 1961. Tallin, 1962, pp. 151-156.
50. Dobrovol'skiy, S.P.: Priroda serebristykh oblakov (The Nature of Noctilucent Clouds). Priroda, No. 3, pp. 87-89, 1964.
51. Suvorov, N.P.: O proiskhozhdenii serebristykh oblakov (The Origin of Noctilucent Clouds). Priroda, No. 12, p. 114, 1964.
52. Grishin, N.I.: Tayna srednikh shirot (The Secret of the Middle Latitudes). Zemlya i Vselennaya, No. 3, pp. 27-33, 1965.
53. Khvostikov, I.A.: Fizika ozonosfery i ionosfery (The Physics of the Ozonosphere and the Ionosphere), in: Ionosfernyye issledovaniya (Ionosphere Studies), No. 11, 1963.
54. Pearse, R., and A. Haydon: Otozhdestvleniye molekulyarnykh spektrov (Identification of Molecular Spectra). Moscow, 1949, p. 178.
55. Grishin, N.I.: Issledovaniya nepreryvnogo spektra serebristykh oblakov (Studies of the Continuous Spectrum of Noctilucent Clouds). Byull. VAGO, No. 19(26), pp. 3-16, 1956.
56. Teplofizicheskiye svoystva veshchestv. Spravochnik (The Thermophysical Properties of Substances. Reference Book). Moscow-Leningrad, 1956.
57. Kurtin, V.: Posledniye dostizheniya v oblasti kondensatsii i ispareniya (Recent Achievements in the Field of Condensation and Evaporation). Raketnaya Tekhnika, No. 6, pp. 3-9, 1961.

58. Shefov, N.N.: Emissiya verkhney atmosfery i serebristyye oblaka (The Emission of the Upper Atmosphere and Noctilucent Clouds), in: Polyarnyye siyaniya i svecheniye nochnogo neba (Aurorae and Airglow), No. 11, 1965, pp. 48-51.
59. Fedynskiy, V.V.: Meteornyye sledy i serebristyye oblaka v verkhnikh sloyakh atmosfery (Meteorites and Noctilucent Clouds in the Upper Layers of the Atmosphere). Meteoritika, No. VII, pp. 95-112, 1950.
60. Dolfus, A.: Vizual'nyye i fotograficheskiye nablyudeniya planet na Pik dyu Midi (Visual and Photographic Observations of Planets on the Pic du Midi), in: Planety i sputniki (Planets and Satellites). Foreign Languages Publishing House, 1963, pp. (494-495) 469-498.
61. Dolfus, A.: Issledovaniye polyarizatsii planet (Studying the Polarization of the Planets), in: Planety i sputniki (Planets and Satellites). Moscow, Foreign Languages Publishing House, 1963, pp. 306-352.
62. Barabashov, N.P., I.K. Koval' and A.T. Chekirda: Nekotoryye rezul'taty fotometrii oblachnykh obrazovaniy na Marse (Some Results of Photometry of the Cloud Formations on Mars). Izvest. Komissii po fizike planet, No. 2, pp. 36-40, 1960.
63. Kellog, W. and K. Sagan: Atmosfery Marsa i Venery (The Atmospheres of Mars and Venus). Moscow, Foreign Language Publishing House, 1962.
64. Sharonov, V.V.: Astron. Tsirkulyar, No. 192, pp. 33-34, 1958.
65. Straut, Ye.K.: Pyatoye mezhvedomstvennoye soveshchaniye po probleme serebristykh oblakov (The Fifth Joint Conference on the Problem of Noctilucent Clouds). Astron. Tsirkulyar, No. 203, p. 19, 1959.
66. Pokrovskiy, K.D.: Svetyashchiyesya nochnyye oblaka (Luminescent Nocturnal Clouds). Izvest. Russkogo Astronomicheskogo Obshehestva, No. 6, pp. 273-289, 1897.

# THE CONDITIONS FOR THE FORMATION AND EXISTENCE OF $H_2O$ MOLECULES IN THE MESOSPHERE

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*ABSTRACT: The conditions for the formation and existence of $H_2O$ molecules in the mesosphere are examined. The analyses show that a general quantitative theory of the photochemical processes in the dynamically active atmosphere can be constructed on the basis of an equation of discontinuity.*

## 1

It is well known that there are two theories on the origin of noctilucent clouds. For the sake of brevity, we will call them the "water theory" and the "dust theory" [1]. The long-term arguments concerning these theories [2] were brought to an end by a discovery resulting from the Swedish-American experiments testing the substance of noctilucent clouds with the aid of rockets [3]. This discovery demonstrated the high humidity of the air in the mesopause during the period when noctilucent clouds appear: ice was found in the composition of the particles in noctilucent clouds. /35

This result is of particular significance in the physics of the atmosphere and outer space. Actually, an experimental confirmation of the dust theory for noctilucent clouds would not have been a great discovery, since the presence of a dust-like substance in the meteor zone of the Earth's atmosphere, constantly introduced by meteors and meteor streams, is a solidly established fact. On the other hand, the possibility that large concentrations of water vapor exist in the mesopause had been refuted by many researchers [1]. We should mention that the water theory assumes (and does not refute) the presence of dust particles in the composition of noctilucent clouds. They are necessary as condensation nuclei. The regular (tropospheric) clouds must necessarily have condensation nuclei in their drops and crystalline particles; moreover, these condensation nuclei must be mainly dust particles. Noctilucent clouds appear in the meteor zone of the atmosphere; thus, it is natural to expect that dust particles of meteoric origin should be the primary condensation nuclei in noctilucent clouds.

However, the interpretation of the results of the Swedish-American experiments cannot be considered conclusive. There is not always a good correspondence between the indications of the instruments on the high-speed rockets and the real properties of

the free atmosphere. The use of rockets for a study of noctilucent clouds necessitates analyses of the theory for interpretations. The circumstances which must be considered in developing this theory have been described in an article written by one of us [4]. The large number of particles found on the day the rocket ascended into the noctilucent clouds can be explained by the fact that dry dust particles flow around the sampler of the rocket together with the incident air flow, while dust particles with ice crusts (which have a greater mass) are attracted less easily by the circumfluent air current. The increase in the meteor activity from August 7 to 11 should also be considered. The effect of the incident flow around the sampler can also explain the increase in the relative percentage of minute dust particles during the ascent /36
into the clouds. The dryness of the small particles can be explained by the effect of a boundary layer of greatly heated air at the nose of the rocket and near the sampler. The yaw of the rocket and the change in the angle of attack should also be considered.

2

The following three conditions are necessary for the appearance of ice particles in the mesopause: (a) the presence of suitable condensation nuclei; (b) a low atmospheric temperature; (c) high humidity of the air.

(a) The problem of condensation nuclei in the mesopause remains unsettled to date. We can assume that the process of condensation of water vapor at very low temperatures (on the order of 130-150°K), with low air pressure and water vapor, differs greatly from the formation of clouds in the troposphere.

(b) The water theory of noctilucent clouds predicted the principal characteristic of the thermal regime of the mesopause: the occurrence of the lowest temperatures of the mesopause during the summer at fairly high latitudes. This conclusion was the natural consequence of a determination of the low temperatures which are necessary for condensation of water vapor in the upper layers of the atmosphere, made by a comparison with the data on the appearance of noctilucent clouds during the summer at fairly high latitudes. In 1961, one of us formulated a general rule which explained the principal characteristics for the distribution of noctilucent clouds by latitude, altitude, and time, from a single point of view: "Noctilucent clouds appear in the atmosphere whereever and whenever the air temperature is sufficiently low" [5].

A rather large number of studies have already examined the thermal regime of the mesopause [5,6]. However, it is still not known what mechanism can bring about such tremendous cooling of the atmosphere [7].

(c) Researchers must also devote their efforts to explaining the high values for the humidity of the air at the level of the mesopause which can be found, apparently, in the zone of noctilucent clouds. This problem will be examined later in more detail.

The most recent studies have indicated that the humidity of the upper stratosphere (above 30 km) and the mesosphere is low, or on the order of $\beta \cong 3 \cdot 10^{-6}$ g/g ($\beta$ is the ratio between the mass of the water vapor and the mass of the air in the same volume) [8]. The problem is further complicated by the process of photodissociation of $H_2O$ molecules by ultraviolet solar rays. The photodissociating solar radiation penetrates into the atmosphere to 70 km, and even to 60 km (low latitudes) during the summer. In the layer of the mesopause from 80 to 85 km, where noctilucent clouds are formed, the concentration of $H_2O$ molecules decreases by $10^3$-$10^5$ times as a result of photodissociation. /37

The decrease in $\beta$ due to photodissociation can be compensated by the effect of a vertical shift of the atmosphere. Above 100 km, the shift can be caused by molecular diffusion. The possibilities for the effect of such a process on aeronomic phenomena in the upper atmosphere of the Earth was first described by one of us in 1935; this assumption was linked with a theoretical explanation for the variations in the intensity of a green OI line ($\lambda$=5577 Å in the airglow spectrum [9]. Subsequently, calculations of the rate of molecular diffusion (also of atomic oxygen) in the thermosphere were published by Nicolet [10] and Mange [11] in relation to the problem of the vertical distribution of molecular and atomic oxygen in the lower thermosphere. The calculations for the diffusion and vertical transport are used in the theory of the vertical structure of the ionosphere [12].

The effect of the dynamic processes on the diurnal changes in the emission intensity of nightglow were examined by V.I.Krasovskiy [13] and Hunten [14]. Hesstvedt [15] published the results of calculations of the vertical transport of $H_2O$ molecules in the mesosphere.

3

There is no general quantitative theory of the photochemical processes in the dynamically active atmosphere at the present. It seems to us that such a theory could be constructed on the basis of an equation of discontinuity.

At altitudes less than 100 km, the coefficient of molecular diffusion is small and the vertical shift of the atmosphere can occur mainly because of turbulent diffusion as well as rising and falling currents. Let $V=V(x,y,z,t)$ be the velocity vector of the currents, and $\rho = n m_{H_2O}$ the density (mass per unit volume) of the water vapor ($m_{H_2O}$ is the mass of $H_2O$ molecules, and $n$ is their number per unit volume). If the $H_2O$ molecules did not disintegrate because of photodissociation, and were not formed by the type of reaction described in [16], then $\rho$ can satisfy the following equation of continuity:

$$\frac{\partial \rho}{\partial t} + \mathrm{div}(\rho \mathbf{V}) = 0. \tag{1}$$

The presence of processes which bring about formation of new $H_2O$ molecules and their disintegration requires introducing the function of the photochemical source $Q = Q(x,y,z,t)$ into (1):

$$\frac{\partial \rho}{\partial t} + \mathrm{div}(\rho \mathbf{V}) = Q, \tag{2}$$

where $Q = R-L$; $R$ is the rate of formation of new $H_2O$ molecules; $L$ is the rate of their disintegration. /38

It is well known that a strongly developed turbulence is observed in the upper mesosphere and the lower thermosphere [16].

The instantaneous values of $\rho$ and $V$ can be represented in the usual way by the following sums:

$$\rho = \bar{\rho} + \rho'; \quad \mathbf{V} = \bar{\mathbf{V}} + \mathbf{V}', \tag{3}$$

where the apostrophe over a character signifies the average with time, and the line over a character signifies the pulsation. Thus, (2) can take the following form:

$$\frac{\partial \rho}{\partial t} + \mathrm{div}(\bar{\rho}\,\bar{\mathbf{V}}) + \mathrm{div}(\overline{\rho' \mathbf{V}'}) = Q. \tag{4}$$

If $\rho_a$ is the density of the atmosphere, then $\rho_a$ and $V_a = V$ should satisfy (1). After replacing the sum of (1) by similar sums in (3), we will obtain the following (disregarding the small term $\rho_a' V'$):

$$\frac{\partial \bar{\rho}_a}{\partial t} + \mathrm{div}(\bar{\rho}_a \bar{\mathbf{V}}) = 0. \tag{5}$$

If we assume that $\partial \rho_a / \partial t = 0$, i.e., that the field of the density of the atmosphere does not depend on the time, and if we assume that this field is horizontally homogeneous and that $\rho_a$ satisfies the equation

$$\rho_a = \rho_{a0} e^{-z/H}, \tag{6}$$

it follows from (5) that

$$\operatorname{div} \bar{V} = -w \frac{\partial \ln \bar{\rho}_a}{\partial z}. \tag{7}$$

The vertical component of the turbulent flow of water vapor $\overline{\rho' w'}$ can take the following form:

$$\overline{\rho' w'} = -K_z \left( \frac{\partial \bar{\rho}}{\partial z} + \frac{\bar{\rho}}{H} \right), \tag{8}$$

where $K_z$ is the coefficient of turbulent diffusion. The second term in the parentheses involves the change in the density of the atmosphere with altitude. Let us demonstrate the validity of (8). In the turbulent atmosphere with a non-zero gradient for the concentration of a certain mixture, the pulsations of the density of this mixture are caused by displacement of the turbulent elements. The value of these pulsations can be calculated by the following relationship:

$$\rho' = -\left[ \frac{\partial \bar{\rho}}{\partial z} - \left( \frac{\partial \rho}{\partial z} \right)_{ins} \right] l', \tag{9}$$

where $\partial \bar{\rho}/\partial z$ is the vertical gradient of the density of the mixture; $(\partial \rho/\partial z)_{ins}$ is the change in the instantaneous density of the mixture in the given eddy during its displacement in the vertical direction; $l'$ is the length of the path of displacement. /39

Let us remember that, by definition, we have the following:

$$K_z = \overline{l' w'}. \tag{10}$$

We can show that, in the atmosphere which satisfies (6), we have the following:

$$\left( \frac{\partial \rho}{\partial z} \right)_{ins} = \frac{\rho}{\rho_a} \frac{\partial \rho_a}{\partial z} = -\frac{\bar{\rho}}{H}. \tag{11}$$

In constructing (11), we assumed that if $\rho$ is the density (concentration) of the water vapor, then the change in $\rho$ inside the turbulent element can occur only as a result of expansion or contraction of the eddy caused by a change in the pressure along the vertical, i.e., we can disregard the effect of the photochemical processes, since the life span of turbulent eddies in the mesosphere is much less (by several orders of magnitude) than the time which characterizes the rate of the photochemical processes. It is easy to see that (8) follows from (9) to (11).

Limiting ourselves to the case of horizontal homogeneous distribution of the water vapor $\left(\frac{\partial\bar{\rho}}{\partial x} = \frac{\partial\bar{\rho}}{\partial y} = 0\text{, from which } \frac{\partial}{\partial x}\overline{\rho' v'} = \frac{\partial\rho' V'}{\partial y}\right)$ and considering Equations (6) to (8), we can present Equation (4) in the following form:

$$\frac{\partial\rho}{\partial t} + w\left(\frac{\partial\rho}{\partial z} + \frac{\rho}{H}\right) - \frac{\partial}{\partial z}\left[K_z\left(\frac{\partial\rho}{\partial z} + \frac{\rho}{H}\right)\right] = Q \qquad (12)$$

(the apostrophes have been omitted).

If we measure the percentage of water vapor by the ratio to the mixture in the following way:

$$\beta = \frac{\rho}{\rho_a},$$

then (12) takes the following form:

$$\frac{\partial\beta}{\partial z} + w\frac{\partial\beta}{\partial z} - \frac{1}{\rho_a}\frac{\partial}{\partial z}\left(A_z\frac{\partial\beta}{\partial z}\right) = Q, \qquad (13)$$

where $A_z = \rho_a K_z$ is the coefficient of the turbulent transfer.

Let us attempt to find the function of the photochemical source, $Q = R - L$, which characterizes the rate of the corresponding photochemical processes. We could have attempted to take the concrete chemical reactions which affect the percentage of water vapor into account for this purpose. However, we can find an approximation for the function of $Q$ by using the rule of relaxation processes which is well known in thermodynamics: the rate of a change in any thermodynamic parameter when the system is tending /40
to equilibrium is proportional to the difference between the instantaneous value of this parameter and its equilibrium value. In the case of water vapor, this leads to the following equation:

$$\frac{\partial \rho}{\partial t} = \alpha(\rho_0 - \rho), \tag{14}$$

where $\rho_0 = \rho_0(z)$ corresponds to the photochemical equilibrium in the atmosphere at rest; $\alpha$ is the factor of proportionality. A solution to (14) has the following form:

$$\rho = \rho_0 + Ce^{-\alpha t},$$

where the integration constant $C$ is determined by the initial conditions (it is equal to the deviation of the initial value for $\rho$ from the equilibrium value). It follows from this solution that $\alpha = 1/\tau$, where $\tau$ is equal to the time during which $C$ decreases by a factor of $e$.

With the calculations for $\tau$ made in the literature [17,18], we can approximate the relationship between $\alpha$ and the altitude by the following formula:

$$\alpha = \alpha_0(1 - \delta e^{-\gamma z}), \tag{15}$$

where $\alpha_0$, $\delta$, and $\gamma$ are constants.

Finally, the equation of discontinuity for water vapor can be written as follows:

$$\frac{\partial \beta}{\partial t} + w\frac{\partial \beta}{\partial z} - \frac{1}{\rho_a}\frac{\partial}{\partial z}\left(A_z \frac{\partial \beta}{\partial z}\right) = \alpha_0(1 - \delta e^{-\gamma z})(\beta_0 - \beta). \tag{16}$$

## 4

It is very difficult to find an analytical solution to such an equation of discontinuity as (16). An evaluation of the order of magnitude of individual terms in this equation shows that, for values of $K_z$ on the order of $10^6$-$10^7$ cm$^2$/sec (frequently observed in higher layers of the atmosphere [16]), the distribution of water vapor becomes stationary very rapidly (in $10^3$-$10^4$ sec). Therefore, it is of practical interest to solve the stationary equation of discontinuity obtained from (16) for $\partial\rho/\partial\tau = 0$:

$$w\frac{d\beta}{dz} - \frac{1}{\rho_a}\frac{d}{dz}\left(A_z \frac{d\beta}{dz}\right) = \alpha_0(1 - \delta e^{-\gamma z})(\beta_0 - \beta). \tag{17}$$

It is easy to find a solution to this equation in the case when $K_z$ = const for the corresponding extreme conditions.

Another extreme case is the atmosphere without turbulence, or $K_z = 0$. In this case, (12) takes on the following form: /41

$$\frac{\partial\beta}{\partial t} + w\frac{\partial\beta}{\partial z} = \alpha_0(1 - \delta e^{-\gamma z})(\beta_0 - \beta). \tag{18}$$

In solving (18), we took the values $\beta = \beta_0$ as the initial conditions; these values corresponded to a photochemical equilibrium in the static atmosphere which we approximated by the exponential function $\beta_0(z) = \overline{\beta}_0 e^{-\mu z}$, where $\overline{\beta}_0$ is the value for the concencentration at the lower boundary of the layer; this is another case of an extreme condition.

At first, we solved (18) for the stationary case $\partial\beta/\partial t = 0$.

Calculated results of the solution which were obtained for the corresponding extreme conditions are shown below:

| $h$ (km) | 72 | 74 | 76 | 78 | 80 | 82 |
|---|---|---|---|---|---|---|
| $\beta$ (for $\omega$ = 0.1 cm/sec) | 0,6 | 0,2 | 0,1 | 0,09 | $3\cdot10^{-2}$ | $8\cdot10^{-3}$ |
| $\beta$ (for $\omega$ = 1 cm/sec) | 1,0 | 0,9 | 0,9 | 0,7 | 0,4 | 0,3 |

[$\beta$ is given in arbitrary units: the value of $\beta_0$ is given as 1 for a height of 70 km above the ground ($z$ = 0)].

Thus, for a relatively low rate of rise $\omega$ = 0.1 cm/sec, the influx of more humid air from a level of 70 km cannot compensate completely for the decrease of $H_2O$ molecules in the mesopause due to photodissociation. However, the velocity of 1 cm/sec is sufficient to maintain the humidity in the mesopause roughly at the same value as that in the lower layers. But how rapidly is the stationary condition established? We also solved (18) for a non-stationary case. The table below shows the distribution of humidity with altitude in the atmosphere at rest and for the presence of a rate of rise equal to 1 cm/sec during the course of one and two weeks.

| h, км | ω=0 | 7 days | 14 days |
|---|---|---|---|
| 70 | 1,0 | 1,0 | 1,0 |
| 72 | 0,4 | 1,0 | 1,0 |
| 74 | 0,2 | 0,9 | 0,9 |
| 76 | 0,08 | 0,6 | 0,7 |
| 78 | 0,04 | 0,3 | 0,7 |
| 80 | $2\cdot10^{-2}$ | 0,1 | 0,4 |
| 82 | $8\cdot10^{-3}$ | 0,04 | 0,3 |
| 84 | $3\cdot10^{-3}$ | 0,02 | 0,07 |
| 86 | $1\cdot10^{-3}$ | $6\cdot10^{-3}$ | $2\cdot10^{-2}$ |
| 90 | $3\cdot10^{-4}$ | $2\cdot10^{-3}$ | $3\cdot10^{-3}$ |
| 100 | $4\cdot10^{-6}$ | $1\cdot10^{-5}$ | $2\cdot10^{-5}$ |

5

The possibility of condensation of the moisture in the mesopause can be explained either by an assumption that the mesopause is cooled off to an extreme degree, or by an assumption that the humidity β increases sporadically. The latter idea can be realized in two ways: either as a result of a sporadic ascent of the masses of humid air from the troposphere through the stratosphere into the mesosphere, or as the result of a formation of additional quantities of $H_2O$ molecules directly in the higher layers of the atmosphere (i.e., as a result of an increase in the level of equilibrium $H_2O$ concentration). Let us examine the latter mechanism in more detail, taking contemporary data on the solar wind into account. /42

As we showed as far back as 1952 [19], the formation of additional quantities of $H_2O$ molecules directly in the higher layers of the atmosphere can be stimulated by corpuscular solar streams, which contain, as we know, a large number of hydrogen atoms. The corresponding increase in the concentration of atomic hydrogen above the equilibrium value could also be the cause of the increase in the concentration of $H_2O$ molecules.

An interesting illustration of this idea is given in the calculations for hydrogen accretion published by de Turville in 1961 [20]. He assumed that the geomagnetic field which is effective in relation to the capture of protons and electrons from the solar wind has a diameter of $\alpha_m = 24.6\ r_E$ ($r_E$ is the radius of the Earth) and that the hydrogen accretion has been occurring for a period of $T = 3.3\cdot10^9$ years at the same rate as during our epoch. In this case, the entire mass of the hydrogen in the mesosphere captured by the geomagnetic field is equal to the following:

$$M = \pi r_m^2 n_1 m_H V_1 T, \tag{19}$$

where $n_1$ is the concentration of hydrogen atoms (protons) in the composition of the plasma of the solar wind; $V_1$ is the velocity of this wind; $m_H$ is the mass of a hydrogen atom. De Turville takes the values $n_1$ = 12 protons/cm$^3$ and $V_1 = 4.33 \cdot 10^8$ cm/sec and obtains the mass $M = 1.70 \cdot 10^{23}$g according to (19). Complete oxidation of this hydrogen would have given $M_1 = 1.53 \cdot 10^{24}$g of water, which is close to the mass of water in the oceans of the Earth ($M_2 = 1.42 \cdot 10^{24}$g). Thus, the water reserves in the ocean could have accumulated gradually by accretion of solar hydrogen in a quantity of roughly 1.5 tons/sec. This mechanism of water accumulation on the Earth with the aid of the solar wind was given the clever name of "solar rain" by Horwitz [21].

However, we cannot consider this very close agreement between the masses $M_1$ and $M_2$ as any more than pure coincidence. The formation of the "solar rain" is a much more complex process than that described in [20]. In an article which has just been published [22], we showed that the value of $M$ which de Turville obtained should be at least $10^3$ times less for a more precise evaluation. The fact is that the plasma stream of the solar wind is not trapped by the Earth's magnetosphere, but flows around it. /43

## 6

Strictly speaking, quantitative evaluations of the accretion of solar protons in the Earth's atmosphere are extremely difficult in the light of the contemporary theory. The theory of solar rain should be considered part of the general theory for a complex of geophysical phenomena: magnetic storms, auroras, radiation belts, the semi-stationary magnetosphere of the Earth. The solar protons in question begin their course toward the Earth with eruptions on the Sun. There is a definite sequence of processes, as a result of which the charged particles move out from the vicinity of the chromosphere and enter interplanetary space. The second chain of phenomena controls the propagation of the particles from the Sun toward the Earth. Finally, there is a sequence of processes in the space around the Earth; this is of direct interest to us. These processes involve the problem of the origin of the radiation belts of the Earth; this is a problem of the interaction between the interplanetary plasma and the geomagnetic field, the capture and movement of protons and electrons in the Earth's magnetosphere. The mechanism for the penetration of charged particles of the solar wind into the Earth's magnetosphere is obviously linked with the great disturbances of the geomagnetic field [23]. Subsequently, the trapped protons enter the plasma of the magnetosphere [24]. From time to time, the charged particles pour out of the magnetosphere into the dense layers of the atmosphere. As V.I. Krasovskiy showed in 1964 [25], the penetration of particles from the corpuscular stream through the boundary of the magnetosphere into the atmosphere, all the way to rather great depths, is apparently inevitable. It is possible that the invasion of the particles at middle and high latitudes occurs in brief flashes (seconds).

There are indications that the low-energy protons (detected by the instruments in the "Explorer XII" satellite) are linked somehow with the soft protons invading the vicinity) of an auroral zone ($L \cong 5$-$7$), when their flux can exceed $10^8$ protons/cm$^2$sec [23]. Using this figure in order to evaluate the intensity of the solar rain, we will assume that their flux can reach values of $10^9$-$10^{10}$ protons/cm$^2$sec during the periods of auroras; considering the length of auroral periods, we will consider that the average value of an arbitrary constant current can reach $10^8$-$10^9$ protons/cm$^2$sec in an auroral zone. The latter value can also be used for a zone of noctilucent clouds in first approximation. This proton flux exceeds the rate of dispersion of terrestrial hydrogen (which corresponds to a flux of $2.5 \cdot 10^7$ hydrogen atoms/cm$^2$sec, according /44 to the calculations of Kockarts and Nicolet [26,27] by a factor of two.

7

If the evaluated value of the flux in a zone of noctilucent clouds, $10^8$-$10^9$ protons/cm$^2$sec, is close to the real value, solar hydrogen can accumulate in the upper atmosphere of the Earth. Let us assume that this hydrogen is being accumulated continuously in the layer at 100-200 km, and that its concentration $n$ (in cm$^{-3}$) is distributed by altitude $z$ according to the following formula:

$$n = n_0 e^{-z/H}.$$

If $H$ were equal to 25 km, the concentration $n_0$ at the level of 100 km would reach values of $n_0 = 1.6 \cdot 10^{10}$cm$^{-3}$ within one year, and values of $n_2 = 4 \cdot 10^8$ cm$^{-3}$ at the level of 200 km. These values greatly exceed the actual concentrations (by a factor of three). Thus, if there actually is a capture of the hydrogen in the solar wind roughly in the same quantities as those mentioned above, there must be a hydrogen leakage from the upper atmosphere of the Earth at a rate of about $10^9$cm$^{-2}$sec$^{-1}$. We have seen earlier that the hydrogen disperses from the exosphere much more slowly. However, it is possible that the hydrogen leaked out of the thermosphere into the mesosphere and subsequently formed solar rain there.

The transformation of solar hydrogen into solar rain is a complex process. The aeronomic reactions which can cause an increase in the concentration of $H_2O$ molecules in the mesosphere have been examined by one of us in a recently-published article [22]. In calculating the concentration $n$ $H_2O$, we must consider the dynamic processes of the falling and rising air currents and the disturbance transfers. In this case, we can use (16) again, since we are concerned with a transfer of photochemically active atmospheric components. Preliminary calculations show that, under certain conditions, the dynamic processes can cause a substantial increase in the humidity of the air in the mesosphere and the mesopause. The fact is that the dynamic processes accelerate the penetration of the solar hydrogen and atomic oxygen from the thermosphere into the denser layers of the atmosphere. This accelerates the reactions, particularly those which occur with triple collisions; for example, the reaction

$$H + H + M \rightarrow H_2 + M + 103.2 \text{ kcal}$$

is greatly accelerated during a transfer of H atoms from a level of 100-120 km to a layer of 80-85 km because of descending currents and disturbance movements. Atomic oxygen is transported downward at the same time; this intensifies the flow of the reactions: /45

$$H_2 + \dot{O} + M \rightarrow H_2O + M.$$

The establishment of a quantitative theory of solar rain is an important task in the physics of the upper layers of the atmosphere. The effect of the dynamic processes must be considered in this theory. The mathematical apparatus for such a theory was shown earlier [an equation of the type in (16)]: an equation of discontinuity for the photochemically active atmosphere. There is no coefficient of molecular diffusion in this equation. However, it should be considered when we examine the processes occurring at altitudes higher than 100 km. The introduction of a term in (16) which considers the vertical dislocation of the atmosphere due to molecular diffusion is not a complicated task.

## REFERENCES

1. Ludlam, F.H.: Noctilucent Clouds. Tellus, Vol. 9, No. 3, 1957.

2. Khvostikov, I.A.: Sovremennoye sostoyaniye problemy serebristykh oblakov (The Present Condition of the Problem of Noctilucent Clouds), in: Rezul'taty MGG, meteorologiya (Results of the IGY, Meteorology), No. 12. Izdat. Akad. Nauk S.S.S.R., 1966.

3. Hemenway, C.L., R.K. Sobserman and G. Witt: Sampling of Noctilucent Cloud Particles. Tellus, Vol. 16, No. 1, pp. 84-88, 1964.

4. Reshetov, V.D. and I.A. Kvostikov: Ob interpretatsii resul' tatov raketnogo zondirovaniya serebristykh oblakov (An Interpretation of the Results of a Rocket Sounding of Noctilucent Clouds), in: Rezul'taty MGG, meteorologiya (Results of the IGY, meteorology), No. 12. "Nauka", 1966.

5. Khvostikov, I.A.: Teplovoy rezhim atmosfery v zone serebristykh oblakov (The Thermal Regime of the Atmosphere in a Zone of Noctilucent Clouds), in: Trudy soveshchaniya po serebristym oblakam v Tartu (Works of a Conference on Noctilucent Clouds in Tartu), Vol. 1. Izdat. Akad. Nauk Est. S.S.R., 1962.

6. Leovy, C.: Radiative Equilibrium of the Mesosphere. J. Atmos. Sci., Vol. 21, No. 3, p. 238, 1964.

7. Kvostikov, I.A.: Vysokiye sloi atmosfery (The High Layers of the Atmosphere). Leningrad, "Gidrometeoizdat", 1964.

8. Badinov, I.Ya., S.D. Andreyev and V.D. Lipatov: Izmereniya vlazhnosti v verkhnikh sloyakh atmosfery (Measurements of Humidity in the Upper Layers of the Atmosphere), in: Rezul'taty MGG, meteorologiya (Results of the IGY, Meteorology), No. 12. "Nauka", 1966.

9. Khvostikov, I.A. and A.A. Lebedev: Variatsii intensivnosti zelenoy linii svecheniya nochnogo neba (Variations in the Intensity of the Green Line in Airglow). Doklady Akad. Nauk S.S.S.R., Vol. 1, No. 2-3, pp. 118-127, 1935.

10. Nicolet, M.: The Aeronomic Problem of Oxygen Dissociation. J. Atmos. and Terr. Phys., Vol. 5, pp. 132-140, 1954.

11. Nicolet, M. and P. Mange: The Dissociation of Oxygen in the High Atmosphere. J. Geophys. Res., Vol. 59, No. 1, pp. 15-45, 1954.

12. Quinn, T.P. and J.S. Nisbet: Recombination and Transportation of the Night-time F Layer of the Ionosphere. J. Geophys. Res., Vol. 70, No. 1, pp. 113-130, 1965.

13. Krasovskiy, V.I.: Proiskhozhdeniye gidroksil'noy sistemy v izluchenii nochnogo neba (The Origination of the Hydroxyl System in Airglow). Uspekhi Fiz. Nauk, Vol. 63, No. 4, pp. 671-691, 1957.

14. Blamont, J.E. and T.M. Donahue: Sodium Dayglow. Observation and Interpretation of the Large Diurnal Variation. J. Geophys. Res., Vol. 69, No. 19, pp. 4093-4127, 1964.

15. Hesstvedt, E.: On the Water Vapor in the High Atmosphere. Geofys. Publikasjoner, Vol. 25, No. 3, 1964

16. Fooks, G.F.: Dynamic Processes in the Lower Ionosphere and their Variation with Height. Ann Géophys., Vol. 20, No. 4, pp. 417-424, 1964. /46

17. Khvostikov, I.A.: Fizika ozonosfery i ionosfery (Physics of the Ozonosphere and the Ionosphere). Izdat. Akad. Nauk S.S.S.R., 1963.

18. Hesstvedt, E.: Some Characteristics of the Oxygen-Hydrogen Atmosphere.Geofys. Publikasjoner, Vol. 26, No. 1, 1965.

19. Khvostikov, I.A.: Serebristyye oblaka i stroyeniye atmosfery (Noctilucent Clouds and the Structure of the Atmosphere), in: Sbornik pamyati Sergeya Ivanovicha Vavilova (Collection Dedicated to Sergey Ivanovich Vavilov). Izdat. Akad. Nauk S.S.S.R., 1952.

20. de Turville, C.M.: Terrestrial Accretion from Solar Wind. Nature, Vol. 190, No. 4771, p. 156, 1961.

21. Out of Thin Air, the Earth's Highest Clouds. NCAR Quart., No. 7, 1964.

22. Khvostikov, I.A.: Priroda serebristykh oblakov i nekotoryye voprosy fotokhimii i dinamiki zemnoy atmosfery (The Nature of Noctilucent Clouds and Some Problems in the Photochemistry and Dynamics of the Earth's Atmosphere), in: Resul'taty MGG, meteorologiya (Results of the IGY, Meteorology), No. 12. "Nauka", 1966.

23. Pletnev, V.D., G.A. Skuridin, V.P. Shalimov and I.N. Shvachunov: O dinamike geomagnitnoy lovushki i proiskhozhdenii radiatsionnykh poyasov Zemli (The Dynamics of the Geomagnetic Trap and the Origins of the Radiation Belts of the Earth). Kosmicheskiye Issledovaniya, Vol. 3, No. 2, pp. 336-339, 1965.

24. Braun, R.R. and J.R. Barcus: Balloon Observation of Auroral Zone X-Rays in Conjugate Regions. J. Geophys. Res., Vol. 70, No. 11, pp. 2599-2612, 1965.

25. Skuridin, G.A. and V.D. Pletnev: Osnovnyye gipotezy o proiskhozhdenii radiatsionnykh poyasov Zemli (The Principal Hypotheses on the Origin of the Radiation Belts of the Earth). Uspekhi Fiz. Nauk, Vol. 85, No. 4, pp. 605-650, 1965.

26. Kockarts, A. and M. Nicolet: Ionospheric Conditions. Ann. Géophys., Vol. 18, p. 269, 1962.

27. Nicolet, M.: Introduction to Chemical Aeronomy. Discussions Faradat Soc., No. 37, pp. 7-20, 1964.

# THE PHYSICS OF THE FORMATION OF NOCTILUCENT CLOUDS, IN THE LIGHT OF NEW DATA

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*ABSTRACT: On the basis of the data from the American-Swedish rocket experiment, it is established that the most probable process ensuring an abrupt temperature decrease in the mesopause and an active entry of moisture is the convective exchange developed by the wave movements in noctilucent clouds.*

According to the data of the Swedish-American experiment [13], the temperature of the mesopause in a layer of noctilucent clouds was -133° in August, 1962. If we consider that under the conditions of such a low temperature, an insignificantly small quantity of water vapor is sufficient for supersaturation and the beginning of sublimation, and that the quantity of sublimation nuclei in the mesopause (as in the troposphere) is always sufficient for cloud formations, the problem of noctilucent clouds essentially involves this question: What process causes such a low temperature in the mesopause? /46

We could mention several processes which could cause a decrease of the temperature in the mesopause. However, their actual role is very unclear at the present. For example, the effect of radiation and cold advection has not been explained sufficiently, and we still do not know the effect of an influx of plasma (according to Villmann's hypothesis [2], it can cause abrupt, although brief, decreases in temperature). Obviously, each of these processes contributes to some extent to the total decrease in temperature preceding the formation of clouds, but none of them (in our opinion) can be considered the principal process. Despite the fact that noctilucent clouds are observed only in certain regions of the Earth, they are a global phenomenon, and their formation should be linked with a process which is developed not within the range of the mesopause alone, but in adjacent regions as well. Like other large-scale processes, this one should be closed with respect to energy, i.e., the cooling in the mesopause should be accompanied by heating in some other layer, or it should be the consequence of such a heating. /47

On the basis of this evaluation of the phenomenon in question, the process which most probably causes formation of noctilucent clouds and is primarily responsible for an abrupt decrease of the temperature in the mesopause is the process of convection, which encompasses the entire mesosphere. Let us examine this process.

It is well known that the mesosphere (from 50-55 to 80 km) is located between two powerful inversions, and is a relatively uniform layer with a vertical temperature gradient of about 0.4°/100 m. In order to determine the degree of stability of this layer, we must consider the dynamic conditions in the vicinity of the inversions.

The lower boundary of the mesosphere is the ozonosphere inversion, which is irradiated by the Sun almost continuously during the summer season (at high latitudes). Naturally, an increase of the temperature on the surface of the inversion can lead to a development of convection. However, wave movements which cannot penetrate into the mesosphere must necessarily be developed on the surface of this inversion. Since there are no clouds at this level, we must confirm the presence of wave movements mainly by the existence of substantial eddies [6]. The greatest amplitudes of the wave movements should be observed over the areas of the Earth's surface which have clear anticyclonic weather and a high temperature, where (according to satellite data [5]) the greatest emission of long-wave radiation capable of heating the ozonosphere occurs. Factual data [10] show that the temperature distribution in the mesosphere (even according to average monthly data) is sometimes adiabatic.

At the upper boundary of the mesosphere, below the thermospheric inversion, the wind is apparently the most important factor which stimulates the activity of the mesosphere. Let us discuss this in more detail.

When noctilucent clouds are present, the wind velocity reaches /48
200 m/sec (according to [13]). However, as we know from observations in the troposphere and stratosphere, exceptionally high wind velocities are concentrated in relatively thin and narrow streams. Observations have actually detected streams in the vicinity of the noctilucent cloud level [11]; according to the data of Doctor Witt[1], the jet streams below the level of minimum temperature in the mesopause are very characteristic for 66°N.

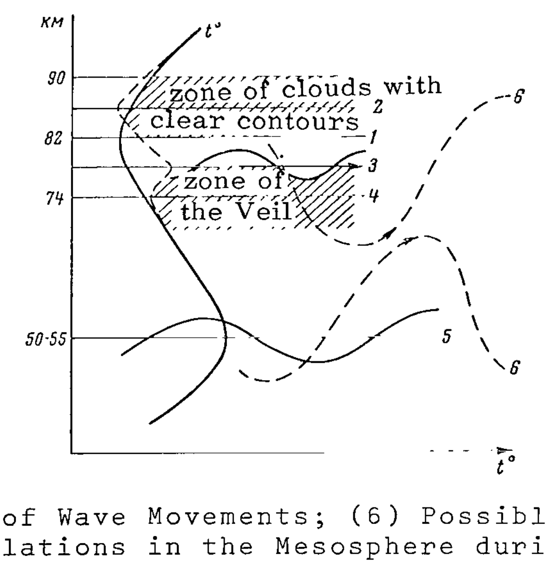
If there is a wind, a turbulent inversion is formed in the vicinity of the maximum wind, most frequently below it [9]; this appears particularly clearly in the system of meso-scale fluxes [12] which are greatly developed, judging by the structure of the cloud cover in the noctilucent clouds. After an additional inversion layer is formed below the thermospheric inversion, a wave movement arises at the upper boundary of this layer; this wave movement also inevitably penetrates the mesosphere (see the figure). We should note in passing that the presently unclarified interrelationship among such phenomena as the wind, inversion, and

[1]According to the materials presented at the International Symposium on Noctilucent Clouds, March, 1966 and kindly made available to the author of this article by Doctor Witt (Sweden).

others noted in the meso-scale processes in the troposphere could aid in making the schematic diagram of the complex mesopause, which I proposed in [8], somewhat more accurate.

First of all, we should consider that the secondary temperature minimum occurring below the level of the principal minimum (see the figure) cannot be as deep as the principal one. The temperature here should be higher, since the secondary minimum is caused by a partial process, i.e., by a turbulence in the zone of the stream. It is very possible that the veil is also formed in the vicinity of the level of the secondary temperature minimum. The veil usually appears earlier than the other forms, below the layer of undulatus [3]. All the other more-developed forms of the clouds (primarily the undulatus forms) are near the principal minimum, which is shifted to a somewhat higher level by the effect of turbulence. As a result of this, the thickness of the cloud layer where the waves appear should increase, and the veil should show signs of the same wave movement. On the other hand, when there is no wind, there is no secondary temperature and also no supplementary inversion. In this case, wave movements cannot develop in the mesopause [8], and only one veil can be observed in the zone of the principal and single temperature minimum.

It is very obvious that the mesosphere can be surrounded by active wave movements arising at its boundaries during certain /49




Zones of Noctilucent Clouds. (1) Level of the Principal Temperature Maximum in a Non-turbulent Mesopause, the Lower Boundary of the Temperature Inversion; (2) Position of the Level of the Principal Temperature Minimum After the Formation of the Secondary Minimum; (3) Position of the Jet Stream below the Level of the Principal Temperature Minimum, the Level of the Most Active Wave Movements in the Mesosphere; (4) Level of the Secondary Temperature Minimum; (5) Upper Boundary of the Ozonospheric Inversion, the Level of Wave Movements; (6) Possible Combination of the Phases of Oscillations in the Mesosphere during the Appearance of Waves with Large Amplitudes.

periods. According to the data of N.I. Grishin [4], the amplitudes of the waves in the layer of noctilucent clouds sometimes reach

20-30 km. When there are such movements (principally meso-scale), and when the lower layer of the mesosphere is greatly heated, an active convective exchange can begin in it. Obviously, we cannot exclude the possibility of a very advantageous coincidence of the phases of oscillations when the upper and lower wave systems can make up a single transmission mechanism for the ascent and descent of large volumes of air through the entire mesosphere (dashed lines in the figure). In any case, the presence of layers with adiabatic stratification within the mesosphere cannot be explained by a regular small-scale turbulence, since the conditions for adiabaticity cannot be maintained in this case.

By the effect of a convective shift occurring adiabatically, the temperature at the lower level of the mesosphere can become equal to 85° (instead of the 10° for the border case) and it can decrease to -165° at the upper level (instead of -90°, for example). This occurs in the case when the air is mixed, at least by half, at /50 all the levels of the mesosphere. With a lesser degree of mixing, the temperature cannot reach these extreme values; when there is no adiabaticity, it cannot change at all.

According to calculated data [10], the velocity of ascending heat currents in the mesosphere can reach 1 m/sec. However, we do not know whether or not this velocity is sufficient to maintain adiabaticity. On the other hand, the velocity of the ascending movements in a wave process (for example, the clouds in the troposphere) reaches 5 m/sec, which ensures adiabaticity to a greater degree.

Thus, a convective shift in the mesosphere, if it occurs with wave movements, best ensures a rather low temperature necessary for cloud formations during certain periods.

Let us examine the values for the water content in noctilucent clouds.

According to [13], the quantity of cloud particles with $d>0.05\mu$ captured by the sampler from a layer from 75 to 95 km is within the limits of $(4-30)\cdot 10^{10}$ per 1 $m^2$ of the surface. Under the condition of uniform distribution, their concentration is $2\cdot 10^6$ per $m^3$ in this case (at least). Assuming that all these particles are ice crystals with $r = 0.3\mu$, the value for the water content (when converted to millibars) is equal to $1.25\cdot 10^{-7}$mb. On the other hand, the extensibility of saturation for a temperature of -133° is only $3.5\cdot 10^{-9}$ mb, i.e., the water content of noctilucent clouds exceeds the value of gaseous water in the clouds by more than one order. The water content in tropospheric clouds is usually only a small fraction of the absolute humidity (excluding individual cases of water content in cumulonimbus).

In order for ice to accumulate in ice crystals, it is necessary that the crystals be colder than the air. Obviously, this is not always the case under the conditions of the rarefied medium in the mesopause. If the humidity in the mesopause has a value on the order of $10^{-7}$mb before the beginning of sublimation, sublimation can continue during the entire period before the temperature decreases to -133°; after this time, the water content can be formed. However, the accumulation of ice in the crystals can also occur in the case when the humidity in the mesopause is less than $10^{-7}$mb. Under the conditions of convection, when water vapors confront the falling crystals with an extensibility of saturation somewhat greater than $3.5 \cdot 10^{-9}$mb, the accumulation of ice can occur even more rapidly than under the conditions of normal diffusion. Thus, the value for the water content in noctilucent clouds agrees completely with the possibility of active convection in the mesosphere.

The idea of convection also agrees with the observed pulsations of the cloud mass, as well as the rapid change in the type of cloud cover mentioned many times in studies by N.I. Grishin [3], and in [7] and [13]. According to [1], the rapid changes in the temperature can explain the disappearance of entire fields of noctilucent clouds during brief intervals of time. However, these changes are also most probable under the conditions of convection. /51

## Conclusions

(1) The values for the temperature and humidity in the mesopause which are necessary for the formation of noctilucent clouds can occur only by the effect of processes which involve the entire mesosphere.

(2) The most probable process which ensures an abrupt temperature decrease in the mesopause and an active entry of moisture is the convective exchange developed with wave movements.

(3) The presence of noctilucent clouds can be a sign of a very active disturbance in the mesosphere.

## REFERENCES


1. Bronshten, V.A.: O prirode serebristykh oblakov (The Nature of Noctilucent Clouds), in: Trudy VI soveshchaniya po serebristym oblakam (Works of the Sixth Conference on Noctilucent Clouds). Riga, 1961.
2. Villmann, C.I.: Nekotoryye soobrazheniya o proiskhozhdenii serebristykh oblakov (Some Ideas Concerning the Origin of Noctilucent Clouds), in: Trudy soveshchaniya po serebristym oblakam (Works of a Conference on Noctilucent Clouds), Vol. III. Tallin, 1962.
3. Grishin, N.I.: Morfologicheskiye issledovaniya serebristykh oblakov (Morphological Studies of Noctilucent Clouds), in: Rezul'taty issledovaniy po programme MGG. Meteorologicheskiye issledovaniya (Results of the Studies in the IGY Program. Meteorological Research), No. 12. "Nauka", 1966.

4. Grishin, N.I.: Morfologicheskiye issledovaniya i priroda serebristykh oblakov (Morphological Studies and the Nature of Noctilucent Clouds) (in this collection).
5. Kondrat'yev, K.Ya.: Nekotoryye problemy interpretatsii rezul'tatov izmereniy ukhodyashchego izlucheniya pri pomoshchi meteorologicheskikh sputnikov (Certain Problems in Interpreting the Results of Measurements of Departing Radiation with the Aid of Meteorological Satellites), Kosmicheskiye Issledovaniya, Vol. 1, No. 1, 1963.
6. Mirtov, B.A.: Dinamika atmosfery i serebristyye oblaka (The Dynamics of the Atmosphere and Noctilucent Clouds), in: Rezul'taty issledovaniy po programme MGG. Meteorologicheskiye issledovaniya (Results of the Studies in the IGY Program. Meteorological Research), No. 12. "Nauka", 1966.
7. Novozhilov, N.I.: Serebristyye oblaka nad Karel'skim peresheykom (Noctilucent Clouds over the Isthmus of Karelia). Priroda, No. 10, 1960.
8. Novozhilov, N.I.: Ob uchete volnovykh dvizheniy v serebristykh oblakakh pri opredelenii struktury mezopauzy (Considering the Wave Movements in Noctilucent Clouds in Determining the Structure of the Mesopause), in: Trudy soveshchaniya po serebristym oblakam, Vol. III. (Works of the Third Conference on Noctilucent Clouds). Tallin, 1962.
9. Novozhilov, N.I.: Turbulentnaya inversiya - rezul'tat deyatel'nosti mezostrui (Turbulent Inversion as the Result of the Activity of a Stream in the Mesosphere). Meteorologiya i Gidrologiya, No. 10, 1963.
10. Khvostikov, I.A.: Vysokiye sloi atmosfery (The Upper Layers of the Atmosphere). Leningrad, "Gidrometeoizdat", 1964.
11. Khvostikov, I.A.: Sovremennoye sostoyaniye problemy serebristykh oblakov (The Present Situation of the Problem of Noctilucent Clouds), in: Rezul'taty issledovaniy po programme MGG. Meteorologicheskiye issledovaniya (Results of the Studies in the IGY Program. Meteorological Research), No. 12. "Nauka", 1966.
12. Kaimal, J.C. and I. Izumi: Vertical Velocity Fluctuations in a Nocturnal Low-Level Jet. J. Appl. Meteorol., Vol. 4, No. 5, 1965.
13. Paton, J.: Noctilucent Clouds. Meteorol. Mag., Vol. 93, No. 1103, 1964.

# THE ROLE OF METEOR PARTICLES IN THE FORMATION OF NOCTILUCENT CLOUDS

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*ABSTRACT: The author of this article examines the quantity and dimensions of the noctilucent cloud particles samples in the Swedish-American experiment. The velocities at which the particles entered the sampler surface of the experimental rockets are also analyzed. It is established that the meteoric-ice hypothesis for the formation of noctilucent clouds can be substantiated by the data from these experiments.*

The concept that the substance of noctilucent clouds is of a cosmic, meteoric origin has been maintained in science for more than 30 years, beginning in 1925. L.A. Kulik [1] first proposed this point of view in 1925, and it was developed in studies by E. Vestine [2], I.S. Astapovich [3], and others. E. Vestine, D. Deirmendjian [4], and C. Hoffmeister defended this idea in their addresses to the Fifth General Assembly of the Special Committee of the IGY in 1958; at almost the same time, F. Ludlam [6] published an article which contained perhaps the most complete discussion and establishment of the meteor hypothesis for the origin of noctilucent clouds. /52

Forty years ago, in 1926, A. Wegener [7] and W. Jardetsky [8] independently suggested that the particles of noctilucent clouds consist of small ice crystals. However, there were no precise data on the temperatures at the level of the mesopause in those years. Indirect calculation methods give greatly increased values, on the order of 300°K [3]. Therefore, the ice hypothesis was not establisted satisfactorily for many years.

From this point of view, the article written by Humphreys in 1933 is of particular interest [8a]. The idea that noctilucent clouds consist of the products of condensation of water vapor into ice crystals at a temperature of about 160°K appeared again in this article. The author gave a purely qualitative schematic diagram for the distribution of temperature with altitude; this diagram was very similar to modern models. Humphreys considered volcanic eruptions as the source of the water vapor at high altitudes; he also felt that these eruptions furnished the condensation nuclei.

In 1952, I.A. Khvostikov [9,10] gave what is now a well-known explanation of the condensation (ice) theory, linking the process of their formation to the temperature minimum in the region of the

mesopause (150-160°K), the presence of which simplifies condensation of water vapor into ice crystals. An explanation was thereby given to the discoveries made long before, concerning the uniformity of the altitude and the small thickness of the layer in which noctilucent clouds can be formed. Subsequently, this concept was developed and supplemented in later works by I.A. Khvostikov [11-19] and myself [20-23]. In particular, I showed (in 1958) the latitudinal and seasonal limits to the appearance of noctilucent clouds by comparing rocket data on the temperature of the mesopause obtained at various latitudes and during various times of the year [22,23]. The temperature distribution by altitude and latitude during the winter and summer (according to Murgatroyd) was presented in a most complete and comprehensive form in [16]. It showed clearly at what altitude, latitude, and season of the year /53
noctilucent clouds can be formed. Other aspects of the condensation hypothesis were presented in great detail in subsequent studies by I.A. Khvostikov [17-19].

In 1950, I suggested the idea that meteor particles act as condensation nuclei in the formation of the ice crystals which make up noctilucent clouds [24]. This idea was examined in more detail in [23] and substantiated and acknowledged by most of the researchers in our country [25-29] as well as abroad [30,31].

The results of the Swedish-American experiments conducted in 1962 were of particular significance in substantiating this hypothesis; in these experiments, particles which clearly belonged to noctilucent clouds were first collected with the aid of special samplers [32-35]. These experiments were described in due time by the Soviet press [36].

Let us recall that a "Nike-Cajun" rocket was launched on August 11, 1962 from the base at Kronogaard (Northern Sweden, $\phi = 66°$, $\lambda = 19°$); the body of this rocket was equipped with a system of samplers intended for catching and studying the following: (a) solid meteor particles, (b) ice crystals, and (c) solid particles with ice deposits on them [32].

The moment the rocket was launched coincided with the appearance of intensive noctilucent clouds over Kronogaard (according to the observations of a more southern station at Kristenberg). A control launching had been conducted on August 7, when there were no noctilucent clouds. Moreover, the bodies of the rockets had their control surfaces shielded from direct impacts of the particles [33].

The particles were collected during the ascending stages of the trajectory, at altitudes of 75-98 km, i.e., immediately in the zone of the noctilucent clouds. An analysis of the materials gave the following results [33].

During the climb on August 11, about $10^7$ particles were collected; the dimensions of the particles ranged from $2 \cdot 10^{-6}$ to $6 \cdot 10^{-5}$ cm. The quantity of particles per unit surface at various sites on the samplers was within the range of $(4\text{-}30) \cdot 10^6$ $cm^{-2}$. During the control climb, the quantity of particles (per unit surface) was 2-3 orders less.

The principal characteristic of the collected particles (found with the aid of electron microphotography) was the lack of a "halo" surrounding the particle (Fig. 1,2); the particle consisted of ice, as a study of the sampler surfaces (made of calcium) showed (these surfaces were designed for a reaction of calcium with water). In Figure 1(a), the small light-colored "tails" of the particles were caused by a "tinting" of a thin film of chromium during pulverization at a small angle to a nitrocellulose sampler surface after the landing. A similar pulverization of an aluminum film was made before the launching.

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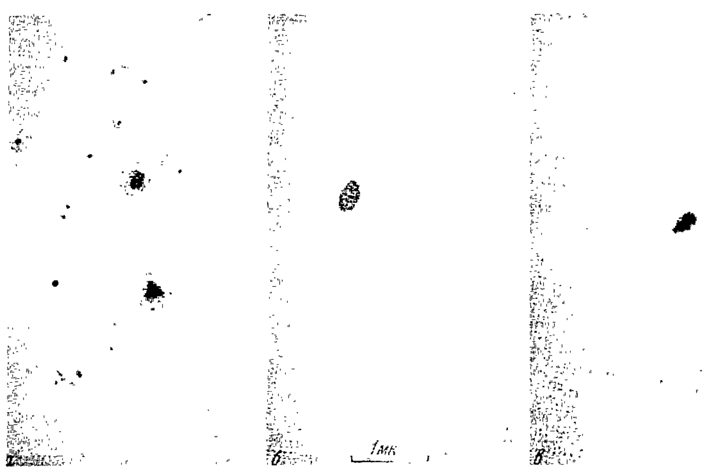

Fig. 1. Particles Collected during the Swedish-American Experiment at an Altitude of 75-98 km (August 11, 1962). (a) Particles of Noctilucent Clouds with "Halos" and one Dim "Tail"; (b) A Particle which Entered the Sampler Surface After the Experiment (No "Tail"); (c) Particle at the Sampler Surface Before the Launching of the Rocket (Two "Tails").

Therefore, the particles entering the sampler surface before the launching should have two "tails" [Fig. 1(c)]; those collected during the launching should have one, and those entering the surface at a later time should not have any "tails." /55


Fig. 2. One of the Particles in the Noctilucent Clouds, Greatly Magnified.

Figure 2 shows one of the particles greatly magnified. We can see round dark inclusions inside the particle. They were found to be most stable during heating as a result of intensive electron bombardment with an energy of 100 KeV.

The distribution of the collected particles by dimensions is shown in Figure 3. It is characteristic that 100% of the particles with $d \gg 1.7 \cdot 10^{-5}$ cm have ice "halos" around them, while only 50% of those with $d = 10^{-5}$ cm have "halos", and none with $d < 7 \cdot 10^{-6}$. Thus, only the particles with $d < 10^{-5}$ cm can serve as condensation nuclei, and their ability to form ice crystals increases greatly as the dimensions increase above this interval.

The presence of iron and nickel in the composition of the most solid particles was found by the method of bombardment with an electron beam; in single cases, the ratio of Ni/Fe reached 0.1. In a study of electron diffraction, the particles showed a characteristic diffraction picture (Laue diffraction pattern) corresponding to twin-crystals with hexagonal symmetry. A recent analysis of the particles has shown a lack of sulphur in them, and a possible absence of silicon, iron, and calcium [37]. However, we will not dwell further on the problem of the chemical composition of the particles because of insufficient data. /56

To clarify the concentration of particles and their size distribution, let us examine the results obtained in the Swedish-american experiments.

First of all, the nature of the interaction between the container and the air flowing around it, as well as the process of the settlement of dust particles on the sampler in dry and humid air should be considered in determining the transition from a concentration of particles on the surface of the sampler to their concentration in nonturbulent air; this was shown correctly by V.D. Reshetov and I.A. Khvostikov [38]. Moreover, it was shown in [38] that the activity of the Perseid shower increased between August 7 and 11, when the number of meteors increased by a factor of 7-10 (in our opinion, this can explain the increase in the number of particles in the experiment on August 11).

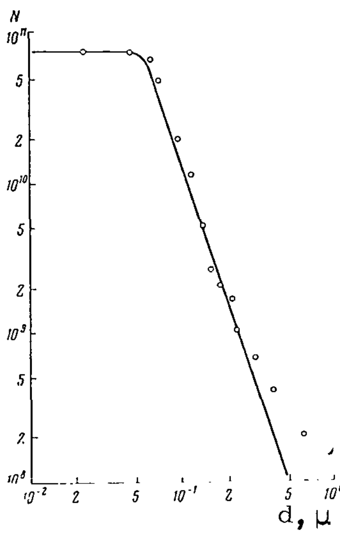


Fig. 3. Distribution of the Particles Collected on August 11, 1962 by Size (The Number of Particles with Diameters Greater than a Certain Size is Shown).

However, the latter concept was established with misunderstandings. The fact is that the increase in the number of meteors in the Perseid shower, which have a relatively high geocentric velocity (60 km/sec), is certainly not synonymous with the increase in the number of meteorites found in the Earth's atmosphere. Fast-moving meteors of the same mass are much brighter and are thus observed in greater numbers than slow meteors. A similar effect, related to meteoric ionization, results in an increase in the number of meteors observed by radar. In general, the role of the meteor streams in the introduction of a substance into the Earth's atmosphere is very modest in comparison to sporadic meteors. Thus, according to B. Yu. Levin [39], the Perseids "supply" the Earth with about 100 kg/day during the maximum period, while sporadic meteors (moving primarily in the same direction as the Earth, and thus having minimum geocentric velocity) "supply" the Earth with much more material (by several orders of magnitude).

Let us now consider the regime of the air flow around the container with the incident flow. We will use the characteristic dimensions of a container $L$ = 1 m, the temperature curve according to the data in [40], and other characteristics of /57
the atmosphere according to [41], and we will calculate the principal characteristics of the streamline flow of the container (see Table 1).

TABLE 1. CHARACTERISTICS OF THE STREAMLINE FLOW OF THE CONTAINER

| $H$, км | $\rho$, g/cm$^3$ | $T$, °K | $l$, см | $\eta$, μ poise | $a$, км/sec | $v$, км/sec |
|---|---|---|---|---|---|---|
| 75 | $4.57\cdot10^{-8}$ | 187 | 0.20 | 115 | 0.274 | 0.83 |
| 80 | $2.06\cdot10^{-8}$ | 162 | 0.43 | 97 | 0.256 | 0.76 |
| 85 | $9.00\cdot10^{-9}$ | 154 | 0.95 | 92 | 0.249 | 0.68 |
| 90 | $3.68\cdot10^{-9}$ | 162 | 2.1 | 97 | 0.256 | 0.60 |
| 95 | $1.55\cdot10^{-9}$ | 180 | 4.5 | 110 | 0.270 | 0.53 |

| $H$, км | Ma | Re | Ma/$\sqrt{\text{Re}}$ | K |
|---|---|---|---|---|
| 75 | 3.03 | $3.30\cdot10^{3}$ | $5.3\cdot10^{-2}$ | $2.0\cdot10^{-3}$ |
| 80 | 2.96 | $1.62\cdot10^{3}$ | $7.4\cdot10^{-2}$ | $4.3\cdot10^{-3}$ |
| 85 | 2.73 | $6.65\cdot10^{2}$ | $9.3\cdot10^{-2}$ | $9.5\cdot10^{-3}$ |
| 90 | 2.35 | $2.28\cdot10^{2}$ | $1.6\cdot10^{-1}$ | $2.1\cdot10^{-2}$ |
| 95 | 1.97 | $7.45\cdot10^{1}$ | $2.3\cdot10^{-1}$ | $4.5\cdot10^{-2}$ |

Note: $l$ is the length of the mean free path of the molecules in the air; $\eta$ is the viscosity; $a$ is the speed of sound; $v$ is the speed of the rocket (according to [34]; Ma, Re, K are the Mach number, the Reynolds number, and the Khudsen number, respectively.

An examination of Table 1 shows that the rocket moved in a glide regime during the stage when the tests were made. Actually, both criteria of this regime,

$$10^{-2} < \text{Ma}/\sqrt{\text{Re}} < 1;$$
$$10^{-2}/\sqrt{\text{Re}} < \text{K} < 1/\sqrt{\text{Re}} \quad (1)$$

are satisfied for the entire stage.

It is well known that a glide course is characterized by the fact that the tangential velocity component of the flow at the surface of the body is low but finite. "At altitudes exceeding 70 km above the Earth, the atmosphere ceases to be a dense gas and resembles a cluster of single molecules bombarding the surface of the rocket in the same way as raindrops. The mean free path of the molecules in the air does remain very small, on the order of several fractions of a centimeter, but we cannot attract the boundary molecules with those adhering to the surface of the rocket. The molecules collide with the surface and rebound from it, slipping past it: we are not saying that the gas begins to slip away." This is how M. Davien describes this regime [42]. /58

In our case, the situation is more complex due to the presence of dust particles in the flow; the dust particles are macroscopic bodies in relation to the molecules in the air, and insignificantly small in relation to the container. For dust particles with dimensions of $10^{-4}$-$10^{-6}$cm, the Knudsen number is $K = 2 \cdot 10^{3}$-$4 \cdot 10^{6}$ and the flow is free-molecular.

All these concepts, as well as those in [38], should be considered in establishing the theory of the experiment, making tests of the particles in noctilucent clouds with the aid of rockets. Although this theory has not been established completely, we can make some approximate evaluations.

In an article by R. Soberman and C. Hemenway, the authors attempted to calculate the flux of meteor particles entering the atmosphere on the basis of the data for the experiment of August 7, 1962 (when there were no noctilucent clouds) as well as a similar launching in the USA on June 6, 1961 (White Sands, New Mexico). In the calculations, the authors considered that the particles lost their cosmic velocity before entering the sampler, and that they were precipitated solely by the effect of the force of gravity, which was partly counterbalanced by the pressure of the molecules encountered in the air. The fringe effects of the streamline flow over the container were not considered. For the experiment of August 7, 1962, it was determined that the flow of particles with $d \gg 3 \cdot 10^{-6}$cm was equal to 0.6 $cm^{-2}sec^{-1}$; for the launching on June 6, 1961, it was established that the flow of particles with $d \gg 10^{-5}$ cm was equal to 0.25 $cm^{-2}sec^{-1}$. The distribution of the particles by size for $5 \cdot 10^{-6} < d < 10^{-4}$ can be described by the following rule:

$$N_D = Ad^{-p}, \tag{2}$$

where $p \approx 2$ (for the particles in the noctilucent clouds with $3 < p < 4$). Therefore, the distribution of particles by mass should be the following (for $p = 2$):

$$N_M = Bm^{-2/3}. \tag{3}$$

In Formulas (2) and (3), $N_D$ and $N_M$ are the number of particles with diameters and masses which exceed the corresponding values of $d$ and $m$.

We should note that in the normal rule for the distribution of meteors [39], $p \cong 3$, and $N_N \sim m^{-1}$. From this point of view, the results of the experiment of August 11, 1962 (when it was determined that $3 < p < 4$) are closer to most of the meteor data.

Although the values of the particle flux for August 11, 1962 were not calculated in [33], we can evaluate the flux of particles with $d \gg 2 \cdot 10^{-6}$ cm by comparing the distributions for $N(d)$ in [33] and [43]; the result is 75 $cm^{-2}sec^{-1}$. Making similar calculations for $d = 10^{-6}$, $10^{-5}$, and $10^{-4}$ cm, we can obtain the following estimates for the particle flux $\phi$, the precipitation rates $v_p$, and the volume concentration of the particles $\chi$ (see Table 2).

TABLE 2. ESTIMATES OF THE FLUX AND CONCENTRATION OF PARTICLES IN THE NOCTILUCENT CLOUDS

| | d, см | | |
|---|---|---|---|
| | $10^{-4}$ | $10^{-5}$ | $10^{-6}$ |
| $v_p$, см/sec | $3 \cdot 10^2$ | 30 | 3 |
| $\varphi$, $см^{-2}$ $sec^{-1}$ | 2.5 | 30 | 75 |
| $\chi$, $см^{-3}$ | $10^{-2}$ | 1 | 25 |
| $\chi_c$ (in[23]) | $2 \cdot 10^{-4}-10^{-2}$ | $2 \cdot 10^{-2}-1$ | 2–100 |
| same [6] | — | $4 \cdot 10^{-2}$ | 4 |
| same [44] | — | $6 \cdot 10^{-1}$ | — |

For the sake of comparison, the lower three rows in Table 2 show the concentrations of particles obtained by myself [23], Ludlam [6], and C. I. Villmann [44]. It is easy to see that the concentrations for August 11, 1962 are close to the marginal limits which I found by analyzing the photometric observations conducted by V.V. Sharonov; they are also close to C.I. Villmann's estimates, and do not exceed Ludlam's.[1] /59

However, since only particles with $d > 10^{-5}$ cm form a "halo" around themselves (as we have already mentioned), the real concentration of particles in the noctilucent clouds (and not meteor particles) for August 11, 1962 did not exceed 1 $cm^{-3}$ (which is roughly one order less than the concentration of particles in cirrus).

In conclusion, we should mention the disappointing misunderstanding described by I.A. Khvostikov [17] concerning the meteoric-ice hypothesis for the formation of noctilucent clouds (which he calls the "compromise" hypothesis described in an article written by myself). Having shown correctly that the water (ice) and the "compromise" hypotheses are essentially the same, and that particles of meteoric origin are the primary condensation nuclei of the particles in noctilucent clouds, I.A. Khvostikov wrote: "the defenders of the water hypothesis have the strange opinion that there are water drops or ice crystals forming in the mesopause without condensation nuclei". He also shows the lack of a basis of such an opinion. Since he has made reference to my works before this [23], I consider it necessary to mention that no such opinion was given in any of my articles (or in the articles of other authors), and thus no repudiation is needed. On the other

[1] The numerical differences in the data in Table 2 and the original studies [6,23,44] can be explained by the transition we made from radii to diameters.

hand, I have attempted to confirm and develop I.A. Khvostikov's theory in my articles [20-24], and I find no divergences from that theory. As for the role of the meteor particles, we have attempted to describe certain aspects of it in this article.

## REFERENCES


1. Kulik, L.A.: K voprosu o svyazi meteoritov s kometami (The Problem of the Relationship between Meteorites and Comets). Mirovedeniye, Vol. 15, No. 2, p. 173, 1926. /60
2. Vestine, E.H.: Noctilucent Clouds. J. Roy. Astron. Soc. Can., Vol. 28, pp. 249-303, 1934.
3. Astopovich, I.S.: Serebristyye oblaka (Noctilucent Clouds). Izvest. Akad. Nauk S.S.S.R., seriya geogr. i geofiz., No. 2, pp. 183-204, 1939.
4. Diermendjian, D. and E.H. Vestine: Some Remarks on the Nature and Origin of Noctilucent Cloud Particles. Planet. and Space Sci., No. 2, 1959.
5. Hoffmeister, C.: Über die "Leuchtenden Nachtwolken" (Noctilucent Clouds). Mitt. d. Sternwarte Sonneberg, No. 41, pp. 7-14, 1953.
6. Ludlam, F.H.: Noctilucent Clouds. Tellus, Vol. 9, No. 3, p. 341, 1957.
7. Wegener, A.: Die Temperatur der obersten Atmospherenschichten (The Temperature of the Highest Atmospheric Layers). Meteorologische Zeitschrift, Vol. 43 (61), No. 10, p. 402, 1926.
8. Jardetsky, W.: Met. Ztschr., Vol. 43 (61), pp. 310-312, 1926.

8a. Humphreys, W.J.: Mother-of-Pearl and Noctilucent Clouds. Monthly Weather Rev., Vol. 61, No. 8, pp. 228-229, 1933.

9. Khvostikov, I.A.: Serebristyye oblaka i stroyeniye stratosfery (Noctilucent Clouds and the Structure of the Stratosphere), in: Sbornik pamyati S.I. Vavilova (Collection Dedicated to S.I. Valivov). Izdat. Akad. Nauk S.S.S.R., 1952.
10. Khvostikov, I.A.: Serebristyye oblaka (Noctilucent Clouds). Priroda, No. 5, pp. 49-59, 1952.
11. Khvostikov, I.A.: O prirode serebristykh oblakov (The Nature of Noctilucent Clouds). Izvest. Akad. Nauk S.S.S.R., seriya geofiz., No. 7, pp. 869-871, 1956.
12. Mikhnevich, V.V. and I.A. Khvostikov: Izucheniye vysokikh sloyev atmosfery (A Study of the Upper Layers of the Atmosphere). Izvest. Akad. Nauk S.S.S.R., seriya geofiz., No. 11, pp. 1393-1409, 1957.
13. Khvostikov, I.A.: Teplovoy rezhim atmosfery v zone serebristykh oblakov (The Thermal Regime of the Atmosphere in the Zone of Noctilucent Clouds), in: Trudy soveshchaniya po serebristym oblakam (Works of a Conference on Noctilucent Clouds), Vol. I,Tartu, 1959, pp. 85-91.

14. Khvostikov, I.A.: O prirode serebristykh oblakov (The Nature of Noctilucent Clouds), in: Nekotoryye problemy meteorologii (Some Problems of Meteorology). Izdat. Akad. Nauk S.S.S.R., 1960, pp. 112-114.
15. Khvostikov, I.A.: Proiskhozhdeniye serebristykh oblakov i temperatura atmosfery v mezopauze (The Origin of Noctilucent Clouds and the Temperature of the Atmosphere in the Mesopause), in: Trudy VI soveshchaniya po serebristym oblakam (Works of the Sixth Conference on Noctilucent Clouds). Riga, 1961, pp. 7-12.
16. Khvostikov, I.A.: Serebristyye oblaka i stroyeniye atmosfery (Noctilucent Clouds and the Structure of the Atmosphere), in: Trudy soveshchaniya po serebristym oblakam (Works of a Conference on Noctilucent Clouds), Vol. III, Tallin, 1962, pp. 7-13.
17. Khvostikov, I.A.: Sovremennoye sostoyaniye problemy serebristykh oblakov (The Present Condition of the Problem of Noctilucent Clouds), in: Meteorologicheskiye issledovaniya (Meteorological Research), No. 12. "Nauka", 1966, pp. 5-10.
18. Khvostikov, I.A.: Priroda serebristykh oblakov (The Nature of Noctilucent Clouds), in: Sovremennyye problemy astronomii i geodezii (Trudy IV s"yezda VAGO) [Present Problems of Astronomy and Geodosy (Works of the Fourth Conference of the All-Union Astronomical and Geodetic Society)]. "Nauka" (unpublished).
19. Kravchenko, I.A. and I.A. Khvostikov: Usloviya obrazovaniya i sushchestvovaniya molekul $H_2O$ v mezosfere (The Conditions for the Formation and Existence of $H_2O$ Molecules in the Mesosphere). This Collection.
20. Bronshten, V.A.: Ob obrazovanii serebristykh oblakov (The Formation of Noctilucent Clouds). Astron. Tsirkulyar, No. 150, pp. 16-17, 1954.
21. Bronshten, V.A.: Priroda serebristykh oblakov (The Nature of Noctilucent Clouds), in: Astronomicheskiy kalendar' na 1958 g (Astronomical Calendar for 1958). "Gostekhizdat", 1957, pp. 211-222.
22. Bronshten, V.A.: O prirode serebristykh oblakov (The Nature of Noctilucent Clouds), in: Nekotoryye problemy meteorologii (Some Problems of Meteorology). Izdat. Akad. Nauk S.S.S.R., 1960, pp. 120-123.
23. Bronshten, V.A.: O prirode serebristykh oblakov (The Nature of Noctilucent Clouds), in: Trudy VI soveshchaniya po serebristym oblakam (Works of the Sixth Conference on Noctilucent Clouds). Riga, 1961, pp. 141-154.
24. Bronshten, V.A.: Yarkiye serebristyye oblaka, nablyudavshiyesya 20-21 iyunya 1950 g. pod Moskvoy (The Bright Noctilucent Clouds Observed over Moscow on June 20-21, 1950). Priroda, No. 11, p. 50, 1950.
25. Morozov, V.M.: K voprosu o proiskhozhdenii serebristykh oblakov (The Problem of the Origin of Noctilucent Clouds). Izvest. Akad. Nauk S.S.S.R., seriya geofiz., No. 7, pp. 865-869, 1956.

26. Teyfel', V.G.: Serebristyye oblaka (Noctilucent Clouds), in: Trudy Sektora astrobotaniki AN Kaz SSR (Works of the Astrobotanical Section of the Academy of Sciences of the Kazan S.S.R.), Vol. V, pp. 59-82, 1957. /61
27. Astapovich, I.S.: Meteornyye yavleniya v atmosfere Zemli (Meteoric Phenomena in the Earth's Atmosphere). "Fizmatgiz", 1958.
28. Khvostikov, I.A.: Vysokiye sloi atmosfery (The Higher Layers of the Atmosphere). "Gidrometizdat", 1964.
29. Grishin, N.I.: Tayna srednikh shirot (The Secret of the Middle Latitudes). Zemlya i Vselennaya, No. 3, pp. 27-33, 1965; also This Collection.
30. Rucnicky, K.: Natura swiecacych oblokow nocnych (The Nature of Noctilucent Clouds). Urania, Vol. 25, No. 12, pp. 376-377, 1954.
31. Pacholczyk, A.: O powstawaniu swiecacych oblokow nocnych (The Appearance of Noctilucent Clouds). Urania, Vol. 26, No. 3, 1955.
32. Soberman, R.K.: Noctilucent Clouds. Sci. American, pp. 50-59, 1963.
33. Witt, G., C.L. Hemenway, and R.K. Soberman: Collection and Analysis of Particles from the Mesopause. COSPAR Fourth International Space Science Symposium, June 1963.
34. Hemenway, C.L., R.K. Soberman and G. Witt: Sampling of Noctilucent Cloud Particles. Tellus, Vol. 16, pp. 84-88, 1964.
35. Hemenway, C.L., E.F. Fullam, R.A. Skrivanek, R.K. Soberman and G. Witt: Electron Microscope Studies of Noctilucent Cloud Particles. Tellus, Vol. 16, pp. 96-102, 1964.
36. Bronshten, V.A.: Rakety izuchayut serebristyye oblaka (Rockets are Studying Noctilucent Clouds). Priroda, No. 1, pp. 95-99, 1964.
37. Skrivanek, R.A.: Chemical Composition of Noctilucent Cloud Particles. Article Presented at the International Symposium on Noctilucent Clouds in Tallin, 1966.
38. Reshetov, V.D. and I.A. Khvostikov: Ob interpretatsii rezul'tatov raketnogo zondirovaniya serebristykh oblakov (Interpreting the Results of a Rocket Sounding of Noctilucent Clouds), in: Meteorologicheskiye issledovaniya (Meteorological Research), No. 12. "Nauka", 1966, pp. 80-83.
39. Levin, B.Yu.: Fizicheskaya teoriya meteorov i meteornoye veshchestvo v solnechnoy sisteme (The Physical Theory of Meteors and the Meteoric Substance in the Solar System). Izdat. Akad. Nauk S.S.S.R., 1956.
40. Mikhnevich, V.V.: Izmereniye davleniya v verkhney atmosfere (Measuring the Pressure in the Upper Atmosphere). Uspekhi Fiz. Nauk, Vol. 63, No. 16, pp. 197-204, 1957.
41. Nicolet, M.: Aeronomiya (Aeronomy). "Mir", 1964.
42. Davien, M.: Techeniya i teploobmen razrezhennykh gazof (The Flow and Heat Exchange of Rarefied Gases). Foreign Language Publishing House, 1962.

43. Soberman, R.K. and C.L. Hemenway: Meteoric Dust in the Upper Atmosphere. J. Geophys. Res., Vol. 70, No. 19, pp. 4943-4939, 1965.

44. Villmann, C.I.: Nekotoryye rezul'taty izucheniya prirody serebristykh oblakov (Some Results of a Study of the Nature of Noctilucent Clouds). Author's Abstract of a Dissertation. Tartu, 1963.

# THE THEORY OF WAVE MOVEMENTS IN NOCTILUCENT CLOUDS

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*ABSTRACT: This article describes an analysis of the wave movements in noctilucent clouds. On the basis of the calculations, the author determined the rate at which the distance between the leading edge and the trailing edge of a noctilucent cloud bank increases.*

## 1. The Formation of Wave Movements in Noctilucent Clouds

In addition to the data from observations of ionospheric drifts and drifts of meteor trails, use of the data from observations of noctilucent clouds is of definite interest in studying the dynamics of the upper atmosphere. It is well known that noctilucent clouds are characterized by the following features: /62

(1) Uniformity of the altitudes at which noctilucent clouds are formed (79-84 km), which has been confirmed by modern stereophotogrammetric measurements [1];

(2) Appearance of noctilucent clouds in a limited latitudinal zone (45-65°) [2];

(3) Seasonal localization for the appearance of noctilucent clouds during the summer [3];

(4) Wave movements in noctilucent clouds.

A factual examination of the spectrum and dynamics of the waves in noctilucent clouds has been conducted in great detail in [4-6].

According to [4-6], very mobile and changing wave formations ("small crests" and "crests") are observed in the field of noctilucent clouds. This is accompanied by a nonuniform distribution of the cloud mass over the wave surface, i.e., consolidation and accumulation of the cloud mass at the crests and a complete or partial evaporation of the clouds at the troughs of the waves. The waves occupy a definite limited area, and show definite dispersion.

In particular, the movement of noctilucent clouds is often interpreted as an actual wind at the peak of the mesosphere. At the same time, there are objections against using a study of the movement of noctilucent clouds as a method of measuring the waves [7]. The values for the wind velocity obtained by observations of noctilucent clouds can sometimes exceed the values for the wind velocity obtained by the meteor method, although the height of the measurements in both cases includes the meteor zone. Since the movement of noctilucent clouds is evaluated according to the movement of the brightest formations, it is possible that the movement of the waves in a field of noctilucent clouds can be mistaken for the movement of the noctilucent clouds themselves, identified with the wind velocity.

The task of this article is to describe the evolution of the distrubances with time, and to establish the wave movements in them, if possible. We will do this on the basis of the initial disturbances of the wind and temperature fields in the mesosphere. /63

We could mention a large number of sources which cause the appearance of temperature and wind anomalies in the zone of the mesopause and the excitation of wave movements in the noctilucent clouds.

(1) As was mentioned in [8] and further developed in [5], the appearance of noctilucent clouds is linked with the meteorological conditions in the troposphere. Thus, an intense increase in pressure was observed in the ground layer of the atmosphere beneath noctilucent clouds in 1950. In 1951, all the noctilucent clouds appeared against the background of an increase in the ground pressure. An analysis of the evolution of the morphology and location of projection of the clouds which coincide with the path of the most active lines for propagation of high pressure shows (according to [6]) the presence of a certain mechanism of interaction between the tropospheric processes and the waves in the mesopause. The flux of energy from the troposphere due to disturbances on a planetary scale ($10^3$ erg$\cdot$cm$^{-3}$ according to calculations in [9]) was examined theoretically in [9]. This work showed that most of their energy is trapped in the troposphere and stratosphere (excluding the periods of the equinox). However, it was shown qualitatively in [5] that gravity waves dispersing upward can be found at the boundary of an anticyclonic formation. According to [10,11], internal gravity waves dispersing upward from the stratosphere can cause the formation of the banks in noctilucent clouds. According to the calculations in [12], the value of the energy flux during the summer period can reach $10^3$-$10^4$ erg$\cdot$sec$^{-1}$cm$^2$ in oscillation frequencies with periods from 7.5 min to 2 hours. Thus, under the conditions of an anticyclonic situation, the orography, convection, and oscillation of the surfaces of a region can excite gravity waves which possibly will leak into the mesosphere and excite the waves in the mesosphere.

(2) The radiation and dynamic processes in the twilight zone are another possible mechanism for the excitation of the waves in a zone of noctilucent clouds. An interpretation and analysis of the results of the orbital measurements with the first

Soviet artificial Earth satellites (1957 β 1, 1958 δ 2, etc.), as well as American satellites [13-15], showed that solar electromagnetic heating shows up in the appearance of an atmospheric expansion on the day side of the Earth, in rising and falling movements of the atmosphere, the amplitude of which depends on the flux of solar short-wave radiation absorbed between 100 and 200 km. Thus, the Earth's atmosphere involved in the Earth's rotation undergoes a thermal disturbance over the illuminated hemisphere, which (according to the theory of the excitation of waves in a stable atmosphere) can generate waves in the atmosphere over the non-illuminated hemisphere; this phenomenon appears in the wave move- /64 ments of noctilucent clouds. According to [6], the changing radiation conditions on the night side cause the appearance of the veil-like form in noctilucent clouds.

(3) The corpuscular heating of the upper atmosphere can also be the source of the temperature and wind anomalies which can excite waves in the upper atmosphere (as we will show later). Even in [16], calculations have shown that the atmosphere is heated during magnetic storms in an auroral zone at the level of the *E* layer with a release of energy of about $2.34 \cdot 10^{-4}$ $erg \cdot sec^{-1} \cdot cm^{-3}$ in a current-carrying layer with a width of 300 km and a thickness of 40 km.

These results were confirmed by the subsequent results of satellite observations. Thus, the author of [17] showed that the increase in the coefficient of the average anomaly $n'$ of the satellite for the quadratic term correlated with the geomagnetic disturbances. Almost all the strong magnetic disturbances corresponded to the increase of $n'$. The results of orbital observations of most of the Soviet and American artificial Earth satellites were analyzed in [18,19], and there was shown to be a great increase in the so-called acceleration of the satellite (decrease in the period of rotation with an increase in the number of turns - the "paradox" of a satellite), $dT/dn$ ($T$ is the period of rotation, $n$ is the number of turns), during magnetic storms (for example, one of which shortened the lifetime of "Sputnik-3" by 10 hours, according to [18]. According to the data obtained, the author of [18,19] constructed the function of the heating of the upper atmosphere; it increased linearly from the mesopause to certain heights in the thermosphere. These data also agreed with the results of the studies in [20,21] which established (as in [18,19]) a direct correlation between the geomagnetic planetary Bartels index and the disturbances of the density in the thermosphere. According to [22-24], the corpuscular heating was caused by the penetration of particles trapped by the geomagnetic field in the so-called Van Allen belts in an auroral zone.

The effect of corpuscular heating was modeled in [25] as a function. The heating changed linearly with the height from zero for $p$ = 0 to maximum for $p$ = 0.1 mb, and increased linearly to zero for $p$ = 0.2 mb; this was found in the area in which the auroral activity was maximum (i.e., in the vicinity of 60°N, or the zone where the ends of the outer radiation belt are "submerged" in the atmosphere).

The "inclusion" of heat sources during magnetic storms, and the subsequent removal of these sources [25], also causes waves in a stable atmosphere (as we will show). The length of these waves is determined by the wind and temperature field. Such waves can be observed in noctilucent clouds.

In relation to this, it is natural to expect that the appearance of noctilucent clouds will be accompanied by geomagnetic and /65 ionospheric disturbances and auroras due to this mechanism of excitation. This was noted by the researchers in [26,27], who observed auroras at the same time as noctilucent clouds.

Spontaneous liberation of the heat of sublimation $Q_{subl}$ of the water vapor on ice nuclei or meteoric nuclei of sublimation can be another possible source of the wave movements in the mesopause, if we hold to the ice hypothesis for the formation of noctilucent clouds [28].

## 2. Theory of the Growth of Ice Particles in the Upper Atmosphere

It is well known that there is an ice hypothesis and a dust hypothesis concerning the formation of noctilucent clouds, as well as a compromise theory according to which the water vapor is sublimated in meteoric nuclei.

According to [29], the dust hypotheses does not explain the localization of the cloud particles at a definite altitude (80-85 km) and latitude and during a definite season, nor does it provide a correlation between the appearance of noctilucent clouds and meteor streams. At the same time, I.A. Khvostikov's diagram explains the stability of the range of altitudes of noctilucent clouds (the pressure of the saturating water vapor $E \ll ap$, where $a$ is the relative percentage of water vapor in the air, $p$ is the pressure of the air, $a$ = 1/4000, $T$ = 150°K [30], the seasonal pattern (the lowest temperatures, about 190°K) are observed at an altitude of 80-85 km during the summer at a latitude of about 65°N [31], and the latitudinal pattern for the appearance of noctilucent clouds (different altitudinal patterns of temperature at low and high latitudes [29]). This agrees with the data presented in Section 1.

According to [32], photometric observations show that the oscillations of the absolute brightness of noctilucent clouds can be explained naturally only by adopting the ice ("condensation") hypothesis. As for the frequency of appearance of noctilucent clouds during the morning and evening, the author of [2] holds the opinion that the observations agree with both the condensation hypothesis and the meteor hypothesis.

In this article, we will be examining the formation of the wave movements in noctilucent clouds from the point of view of the condensation and dust hypotheses.

According to [33], the growth rate of small ice particles at a low pressure can be determined by the following equation:

$$\frac{dr}{dt} = \frac{a}{\rho_{ice}\sqrt{2\pi R_W T}}\left[e - e_{ice}(r)\right], \tag{1}$$

where $a$ is the coefficient of sublimation; $\rho_{ice}$ is the density of the ice; $R_W$ is the gas constant of the water vapor; $e$ is the ambient pressure of the water vapor; $e_{ice}(r)$ is the equilibrium vapor pressure above an ice sphere with radius $r$; $T$ is the temperature. If there were no sublimation, we would have the following: /66

$$e = e_0\left(\frac{T}{T_0}\right)^{7/2}.$$

Here, $T_0$ is the freezing point. However, the decrease in the pressure of the water vapor $e^*$ caused by sublimation is the following:

$$\frac{e^*}{R_W T} = N\rho_{ice}\frac{4\pi}{3}(r^3 - r_{nuc}^3),$$

where $N$ is the number of cloud particles per unit volume; $r_{nuc}$ is the radius of the sublimation nuclei which can be particles of a meteoric origin accumulated in the mesopause, so that according to [33],

$$e = e_0\left(\frac{T}{T_0}\right)^{7/2} - NR_W T\rho_{ice}\frac{4\pi}{3}(r_2 - r_{nuc}^3). \tag{2}$$

The temperature change in the pressure of the water vapor above the ice can be described by the Clausius-Clapeyron equation,

$$\frac{de_{ice}}{dT} = \frac{Q_{subl}e_{ice}}{R_W T^2}$$

so that we have the following:

$$e_{ice} = e_0 \exp\left[-\frac{Q_{subl}}{R_W}\left(\frac{1}{T}-\frac{1}{T_0}\right)\right]. \tag{3}$$

Considering the change in the pressure of the water vapor above an ice particle with an effective radius of

$$e_{ice}(r) = e_{ice} \exp \frac{2\sigma}{\rho_{ice} R_W T r},$$

where σ is the surface energy at the ice-vapor boundary. After using (3), we will obtain the following:

$$e_{ice}(r) = e_0 \exp\left[\frac{2\sigma}{\rho_{ice} R_W T r} - \frac{Q_{subl}}{R_W}\left(\frac{1}{T}-\frac{1}{T_0}\right)\right]. \tag{4}$$

Substituting (2) and (4) into (1), and making simplifications in view of the small number of ice particles per unit volume of air, we will obtain the following [33]:

$$\frac{dr}{dt} = \frac{ae_0}{\rho_{ice}\sqrt{2\pi R_W T_0}} I, \tag{5}$$

where

$$I = \left(\frac{T}{T_0}\right)^3 - \sqrt{\frac{T_0}{T}} \exp\left[\frac{2\sigma}{\rho_{ice} R_W T r} - \frac{Q_{subl}}{R_W}\left(\frac{1}{T}-\frac{1}{T_0}\right)\right]. \tag{6}$$ /67

Equation (5), which was obtained from [33], links the rate of growth (and evaporation) of the ice particles to the temperature of the menopause. With a certain altitude distribution of the temperature in the mesopause $\overline{T}(z)$, there can be ice crystals with a radius $r$ determined by (6) in reaching the temperature $\overline{T}(z)$. Let us examine the changes in the growth of crystals contributed by disturbances in the static field of the temperature $\overline{T}(z)$. In view of the small number of these disturbances (the factors enumerated in Section 1), we can linearize (6) in relation to the temperature, and

$$\frac{dr'}{dt} = -\alpha T', \tag{7}$$

where

$$r' = r - \overline{r}; \quad T' = T - \overline{T};$$

$$\alpha = \sqrt{\frac{\overline{T}_0}{T}\frac{1}{T}\left(\frac{Q_{\text{subl}}}{R_{\text{W}}T} - \frac{1}{2}\right)\exp\left[\frac{2\sigma}{\rho_{\text{ice}} R_{\text{W}} T_0 r} - \right.} \\ \left. - \frac{Q_{\text{subl}}}{R_{\text{W}}}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] - 3\left(\frac{\overline{T}}{T_0}\right)^2 \frac{1}{T_0}.$$

We can see from the simple expression obtained for the growth rate of ice crystals that, in order to describe the distribution of the elements in noctilucent clouds in time and space, it is necessary to have data concerning the disturbances of the temperature field in the mesosphere.

## 3. Determining the Evolution of the Disturbances in the Wind and Temperature Fields and Their Relationship to the Growth of Ice Crystals

In order to calculate the temperature disturbances, we will use the equation of heat balance in the following form:

$$\frac{dT'}{dt} = -\beta w + \nu \Delta T', \tag{8}$$

where $\beta = \gamma_a - \gamma$; $\gamma_a$ is the dry adiabatic temperature gradient; $\gamma$ is the vertical temperature gradient in the mesopause; $\nu$ is the coefficient of the turbulent mixing;

$$\frac{d}{dt} = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + w\frac{\partial}{\partial z};$$

$u$ is the wind velocity component in the direction of the horizontal axis $x$; $\omega$ is the vertical wind velocity; /68

$$\Delta = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2}.$$

According to [34-36], the combination of facts obtained from radar and rocket observations indicates that the atmosphere up to altitudes on the order of 100 km is in a state of turbulent mixing. On the basis of these factual materials, the processes of dissipation are described in (8) with the aid of a semi-empirical theory of the turbulence with the mixing coefficient $\nu$, which (according to the data presented in [34-36] has an average value of $\nu = 10^4$-$10^5$ cm$^2$/sec at an altitude of 90 km. According to [37], it is possible that Helmholtz waves are observed in noctilucent clouds below a strong inversion beginning at an altitude of 83-85 km.

However, in contrast to tropospheric waves (according to [37]), these waves do not regenerate into cellular convection. At the same time, there can be cellular convection in the immediate vicinity of the peak of the mesosphere, according to [38]. This is also confirmed by stereophotogrammetric observations [39] of noctilucent clouds, where convective granulation is noted. In view of this, (8) was written as a simplification of the convection theory, where the term ($-\beta\ \omega$) describes the necessary convection caused by the vertical stratification of the mesopause. The heat flux for the volume in question was not considered in (8); the heat flux excites the established condition and is used as the initial condition.

As we can see from (8), it is necessary to calculate the wind field in order to determine the temperature disturbances. In works involving the theory of cloud formation (for example, in [40,41] and in [33], but not in [42,43]), this field is given as certain functions of $u$ and $\omega$ which generally depend on the altitude. In this study, the wind field will be calculated by the equations for movement under the initial conditions determined by the disturbances (however, we will not consider the "push-pull" effect of the cloud formed in the wind field, which was stipulated earlier).

We will also write the equations for the movement with the so-called simplifications of the theory of free convection (in the original condition, the temperature and pressure fields are assumed to depend only on the altitude, and the dynamic terms are linearized in the form used in [42], with the one exception that we will consider the unsteady state of the process, the viscosity, and the presence of a steering current. Moreover, in contrast to the equation in [44], we will not use the simplifications of the theory of long waves:

$$\frac{\partial u}{\partial t} = -R\overline{T}\frac{\partial}{\partial x}\frac{p}{P} + \nu\Delta u;$$

$$\frac{\partial w}{\partial t} = -R\overline{T}\frac{\partial}{\partial z}\frac{p}{P} + \alpha T' + \nu\Delta w; \qquad (9)$$

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$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0,$$

where $p$ is the divergence of the pressure from the static $P$; $\alpha = g/T$ is the Archimedean force caused by the horizontal temperature nonuniformity of the mesosphere in the field of gravity with an acceleration of $g$.

Introducing the function of the current $\varphi$ by means of the following relationships,

$$u = -\frac{\partial \psi}{\partial z}; \quad w = \frac{\partial \psi}{\partial x}$$

and including the incident flow,

$$\overline{u}(z) = -\frac{d\overline{\psi}}{\partial z}; \; \psi(x, z, t) = \overline{\psi}(z) + \psi'(x, z, t), \tag{11}$$

where $\psi'$ is not considered small in comparison to $\overline{\psi}$, and substituting (10) and (11) into (9), we will obtain the following:

$$\begin{gathered}\frac{\partial \Delta \psi'}{\partial t} + \widetilde{u}\frac{\partial \Delta \psi'}{\partial x} - \widetilde{u}_{zz}\frac{\partial \psi'}{\partial x} - \alpha\frac{\partial T'}{\partial x} = (\Delta\psi', \psi') + \nu\Delta\Delta\psi'; \\ \frac{\partial T'}{\partial t} + \widetilde{u}\frac{\partial T'}{\partial x} + \beta\frac{\partial \psi'}{\partial x} = (T', \psi') + \nu'\Delta T',\end{gathered} \tag{12}$$

where

$$\widetilde{u}, \; \widetilde{u}_{zz} \equiv \widetilde{\frac{d^2u}{dz^2}}$$

are the average wind and vertical gradient of the change in the wind with altitude in the mesopause; we can also use the following symbols:

$$(a, \; b) = \frac{\partial a}{\partial x}\frac{\partial b}{\partial z} - \frac{\partial a}{\partial z}\frac{\partial b}{\partial x}.$$

When there is an incident wind flow and a vertical temperature stratification, we should consider the anisotropy of the space in relation to the propagation of the gravitational disturbances. This causes a horizontal movement of the disturbance front. In addition to these necessary factors (horizontal wind, horizontal isothermal surfaces), the clearly-expressed directionality of the gravitational forces limits the movement of the horizontal plane [45,46]. We will assume that the propagation of the disturbances from the source occurs in this ease (as in the unidimensional case) in the direction of the $x$-axis. The dependence on time, with an accuracy up to the dimensional coefficient (in phase velocity $c$) is the same as the dependence on the spatial coordinate $x$ [47]. In relation to this, we will determine the class of solutions to system (12) by analogy with the famous solutions to the plane /70
barotropic vorticity equation in [48,49]. The solutions take the form of a superposition of plane waves, i.e.,

$$\psi'(x, z, t) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} \psi_{mn} e^{i\frac{2\pi}{L_1}m(x-ct) + \frac{2\pi}{L_2}nz - \delta t} \tag{13}$$

under the conditions that

$$\delta = \nu(m_1^2 + n_1^2) = \text{const}, \; m_1 = \frac{2\pi}{L_1} m, \; n_1 = \frac{2\pi}{L_2} n. \tag{14}$$

According to (13), the operator of the local differentiation can be presented in the following way [50]:

$$\frac{\partial}{\partial t} = -c\frac{\partial}{\partial x_1} - \delta, \tag{15}$$

where

$$x_1 = x - ct \tag{16}$$

and the system in (12) can be written in the following form:

$$\begin{gathered} \frac{\partial}{\partial x_1}[(\tilde{u} - c)\Delta\psi' - \tilde{u}_{zz}\psi'] - (\delta + \nu\Delta)\Delta\psi' - \alpha\frac{\partial T'}{\partial x_1} = (\Delta\psi', \psi'); \\ \frac{\partial}{\partial x_1}(\tilde{u} - c)T' + \beta\frac{\partial\psi'}{x_1} - (\delta + \nu\Delta)T' = (T', \psi'). \end{gathered} \tag{17}$$

In view of (13), we have the following:

$$\Delta\psi' = -\mu^2\psi', \tag{18}$$

where

$$\mu^2 = m_1^2 + n_1^2 = \text{const}. \tag{14'}$$

In [44] and [51], the solutions to a system similar to (17) are found with the aid of the first integrals. We will also use this method here. It follows from [44,51,52] that the nonlinear system in (17) can be reduced to a solution of a linear equation if $\Delta\psi'$ and $T'$ are linear functions of $\psi'$. This requirement can be satisfied according to (18) for $\Delta\psi'$. In order to obtain an analytical solution, we will also use the following function (by analogy):

$$T' = \tau\psi'. \tag{19}$$

Substituting (18) and (19) into (17), we will find that

$$\tau = -\frac{\beta}{\tilde{u} - c}, \tag{20}$$

where the phase velocity $c$ is determined by the dispersion equation, /71

$$\tilde{u}_{zz} + (\tilde{u} + c)\mu^2 - \frac{\alpha\beta}{\tilde{u} - c} = 0. \tag{21}$$

It roots are the following:

$$c_{1,2} = \tilde{u} + \frac{1}{2}\frac{\tilde{u}_{zz}}{\mu^2} \pm \frac{1}{\mu}\sqrt{\frac{\tilde{u}_{zz}^2}{4\mu^2} + \alpha\beta}. \tag{22}$$

These two roots can be used for constructing two solutions of the following type:

$$\psi'_{mn} = e^{im_1(x - c_1 t) + inz - \delta t};$$
$$\psi''_{mn} = e^{im_1(x - c_2 t) + inz - \delta t}. \tag{23}$$

According to (13), the superposition of these solutions can be solved by (18) in the following way:

$$\psi'(x, z, t) = \frac{1}{2}\sum_m \sum_n \psi_{omn}(\psi'_{mn} + \psi''_{mn}), \tag{24}$$

where $\psi_{0mn}$ is the Fourier coefficient of the initial disturbance.

Since the phase velocity has two values [according to (22)] which correspond to two elementary waves, $\psi'_{mn}$ and $\psi''_{mn}$, the disturbances of the temperature can be determined according to (19) by an expression which is similar to (24):

$$T'(x, z, t) = \frac{1}{2}\sum_m \sum_n \psi_{omn}(\tau'\psi'_{mn} + \tau''\psi''_{mn}), \tag{25}$$

where

$$\tau' = -\frac{\beta}{\tilde{u} - c_1}; \quad \tau'' = -\frac{\beta}{\tilde{u} - c_2}. \tag{26}$$

It is easy to see that (24) and (25) satisfy (17) under the conditions (14), (18), (14'), and (21). Conditions (14) and (14') are important characteristics of each wave packet, since the velocity of the packet is determined by them according to (22). Thus, all the harmonics in the wave packet are moved at one phase velocity characteristic of the given packet. We should note that each harmonic moves at a different velocity, which causes their nonlinear interaction and the "leakage" of the packet [54].

It was mentioned in [33] that (1) determines the radius of the icy cloud elements with an accuracy up to a constant $r$ determined by the nonturbulent condition. Using this fact to determine the initial radius of the ice elements, we will find the following [by substituting (25) into (7) and squaring the elements] /72

$$r' = \frac{\alpha}{2} \sum_m \sum_n \psi_{omn} (\tau^{*'} \psi^{*'}_{mn} + \tau^{*''} \psi^{*''}), \qquad (27)$$

where $\tau^{*\prime}$ and $\tau^{*\prime\prime}$ differ from (26) by the presence of corresponding factors $[m_1(u-c_{1,2})]^{-1}$, while $\psi^{*\prime}$ and $\psi^{*\prime\prime}$ are characterized by the change in the phases by $\pi/2$. As we have mentioned earlier, the ice hypothesis is being accepted in this study; (27) gives the evolution of the radius of the ice particles in relation to the initial radius, which was determined by the initial thermohydrodynamic disturbances and the size of meteor particles, since the value of $r_{nuc}$ introduced in (2) (according to the rocket soudings of noctilucent clouds [55]) is apparently determined by the spectrum of the meteor dust.

If we use the dust hypothesis, the distribution of the density of particles $n$ per unit volume can be described by the equation in [56]:

$$\frac{\partial n}{\partial t} = -\frac{\partial}{\partial x}[n(\bar{u} + u')] - \frac{\partial (nw')}{\partial z}, \qquad (28)$$

where $u'$ and $\omega'$ can be determined by (15), (16), and (29), i.e., by using the dust theory. It is not necessary to determine the temperature disturbances or to use Formula (27). If we have the following:

$$\int_{-h}^{0} n dz = \tilde{n} h = N,$$

then, according to [56],

$$\frac{\partial N}{\partial t} + \tilde{u} \frac{\partial N}{\partial x} = -\tilde{n} \int_{-h}^{0} \frac{\partial u'}{\partial x} dz. \qquad (29)$$

Converting (13) and (14), we will obtain the following:

$$N(x, z, t) = \frac{1}{2}\tilde{n}\psi', \tag{30}$$

where $\psi'$ is determined by (24).

Since the number of particles along the line of sight is proportional to $h$, we can expect the appearance of wave billows in them in observing noctilucent clouds from the Earth (according to [31]).

## 4. Analysis of the Wave Movements in Noctilucent Clouds

When the percentage of sublimation nuclei per unit volume is fixed, the radius of the ice particles increases as the noctilucent cloud becomes more dense and more bright. We can see from (27) that the distribution of the cloud mass can be described by the superposition of two waves, one of which always moves in the direction of the oncoming wind, and the other of which moves either in the same direction as the first wave, remaining some distance from it, or even in the opposite direction, depending on the length of the wave in the cloud. /73

In order to analyze the wave movements in noctilucent clouds and the structure of the mesopause, the author of [57] proposed using the famous parameter of A.A. Dorodnitsyn [58]:

$$l^2 = \frac{1}{\tilde{u}^2}\frac{g}{T}(\gamma_a - \gamma) - \frac{1}{\tilde{u}}\frac{d^2u}{dz^2}. \tag{31}$$

As we can see from (19), this parameter is a partial case of a steady movement, and it characterizes $\mu$ in the stationary case, when $c = 0$ (the "inherent frequency" of the mesopause):

$$\mu^2_{\text{stat}} = \frac{\alpha\beta}{\tilde{u}^2} - \frac{1}{\tilde{u}}\frac{d^2u}{dz^2}.$$

When there is no oncoming flow, we have the following:

$$\tilde{u} = \frac{\widetilde{d^2u}}{dz^2} = 0$$

The disturbance can be described by the waves which are going out in various directions from the disturbance source, in correspondence with the following expression:

$$c_{1,2} = \pm\frac{1}{\mu_{mn}}\sqrt{\alpha\beta}, \tag{32}$$

In other words, the rate of propagation of these waves is determined solely by the temperature stratification of the atmosphere and the dimensions of the wave.

We can see from (20) for the phase velocity of the waves that, if the first term in (20) is greater than the second, then the waves move with the flow, or are "blown" along by the flow, i.e., for

$$\frac{1}{\mu_{mn}}\sqrt{\frac{\widetilde{u}_{zz}}{4\mu_{mn}^2}+\alpha\beta}<\widetilde{u}+\frac{\widetilde{u}_{zz}}{2\mu_{mn}^2}$$

or

$$\mu_{mn}^2>\frac{\alpha\beta}{\widetilde{u}^2}-\frac{\widetilde{u}_{zz}}{\widetilde{u}}=\mu^2_{\text{stat}} \qquad (33)$$

Thus, if the wave number of the wave is greater than the wave number of a stationary wave determined by $l^2$[58], or if the wave length is less than the length of the steadied wave (characteristic of the given flow) (which is the same thing), the first wave will move with the wind. Thus, short waves in noctilucent clouds (or "small crests" according to the generally-accepted classification of N.I. Grishin) move with the wind which prevails at the level of the mesopause. /74

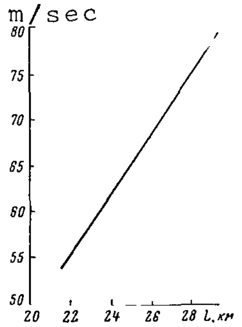


Fig. 1. Diagram of the Change in the Phase Velocity as a Function of the Wavelength for 4 min 10 sec for One Group of Crests in Noctilucent Clouds Observed on July 20-21, 1965.

As for the waves which are longer than the characteristic wavelength of the given condition of the mesopause, these waves can move in the windward direction. In this case, it follows from (33) that:

$$\mu^2<\mu^2_{\text{stat}} \qquad (34)$$

The author of [39] mentioned that the long waves ($L_1$>50 km) in the observed broad field of noctilucent clouds moved in a direction which was almost opposite to the movement of the cloud system, and the small crests (5<$L_1$<10 km) moved with the cloud system.

The data from observations of the velocity of movement of waves with different dimensions in noctilucent clouds were subjected to a very detailed analysis in [5]. The results of this analysis were presented in the form of a relationship between the phase velocity and the wavelength. If the movement of the leading edge of the crests can be described by the simple formula which follows from (20),

$$c = \tilde{u} + \frac{L}{2\pi}\sqrt{\alpha\beta}, \tag{35}$$

then the relationship between the phase velocity and the wavelength can be described approximately by a linear function. As we can see from Figure 1, the results of [4] also give a linear dependence for short intervals of time. According to (35) and Figure 1, we can determine the wind velocity and the parameter of the stability in the mesopause on July 20-21, 1955:

$$\tilde{u} = 15 \text{ m/sec}; \sqrt{\alpha\beta} = 2 \cdot 10^{-2} \text{ sec}^{-1}. \tag{36}$$

The data for the parameter of stability in the lower ionosphere are given in [12] as $\approx 0.02$ sec$^{-1}$. According to the data in [59], the average zonal wind component at an altitude of 80 km during the summer has a value from 10 m/sec (Jodrell Bank) to 25 m/sec (Adelaide). I should like to mention that the wind velocity for lower altitudes reaches $\approx$ 50 m/sec (60 km); for higher altitudes, it reaches $\approx$ 65 m/sec (100 km). Therefore, the data obtained from (36) agree satisfactorily with the results of rocket and radiometeoric observations. I will also mention that the wind velocity in the mesopause during the summer, as determined in [59], never reaches values of 55-80 m/sec (the phase velocities of the movement of crests in noctilucent clouds). However, we can see from (35) that, with a decrease in the wavelength, the phase velocity of movement of the "small crests" is close to the real movement of a neutral atmosphere in the lower ionosphere. This also /75
conforms with the results of [4]. It follows from (20) that the difference in the phase velocities of the waves is the following;

$$c_1 - c_2 = \frac{1}{\mu_{mn}}\sqrt{\frac{\tilde{u}_{zz}^2}{4\mu_{mn}^2} + \alpha\beta}. \tag{37}$$

Thus, the difference between the leading edge and the trailing edge of the cloud bank increases at a rate determined by (37) or the tangent angle of inclination of the line in the figure. This fact also corresponds to observations [4].

Comparing formulas (25) and (28), we can see that the phase of the cloud mass shifts relative to the wind flow by $\pi/2$, i.e., the cloud mass of noctilucent clouds is concentrated on the leeward side of the wind crest. This change in the phase is similar to the hysteresis in the appearance of lenticular clouds in relation to the leeward waves, i.e., the appearance of a cloud during its ascent lags in the same way as does its disappearance during descent; this coincides with the results in [60,61].

As we can see from (31), the phase shift does not follow from the theory, if we use the dust hypothesis. Obviously, the explanation of the actual phase relationships can aid in identifying the nature of the matter of the elements in noctilucent clouds.

We can see from (28) that the evolution of a cloud can be described by the movement of two waves with different amplitudes.

If we disregard the effect of the temperature stratification (i.e., consider the stratification of the mesopause to be insignificant) then (39) becomes equal to zero, and the cloud moves with the flow at the velocity of the wind.

## 5. Conclusion

It was maintained in [4] that "an analysis of the existing methods and results of analysis found in literature for the 'drift' of noctilucent clouds shows that the authors have frequently measured the phase velocity of single details, or the rate of movement of the entire wave field, and that they have interpreted this as the migratory motion which directly indicates the value of the wind velocity at the level of the noctilucent clouds, so that various authors give values from 10 to 300 m/sec for the value of the 'drift velocity' of the noctilucent clouds".

The analysis conducted here shows that, in addition to the incident wind, the thermal stratification of the upper atmosphere, the Archimedean forces, and the change in the wind shift with the altitude have a substantial effect on the drift of noctilucent clouds. Therefore, in determining the wind velocity in the meteor zone by the drift of the noctilucent clouds, we should consider the /76
following factors, we well as the magnitude of the waves.

(1) When there are temperature and wind disturbances caused by internal gravity waves and electromagnetic and corpuscular heating of the Sun, there are waves in the mesopause which, under the favorable conditions determined by I.A. Khvostikov's diagram, enter the dynamics of the noctilucent clouds.

(2) The phase velocity of movement of the leading edge of a wave in noctilucent clouds greatly exceeds the actual wind velocity.

(3) The visible wavelength of noctilucent clouds increases with time.

(4) Larger waves can move against the wind flow.

(5) The visible mass of noctilucent clouds advances the wind flow, and is concentrated at the leeward sides of the crests of the atmospheric waves.

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## REFERENCES

1. Burov, M.I.: Opredeleniye vysot serebristykh oblakov stereofotogrammetricheskim sposobom (Determining the Heights of Noctilucent Clouds by Stereophotogrammetric Methods). Dissertation, Moscow, 1962.
2. Pavlova, T.D.: Vidimaya chastota poyavleniya serebristykh oblakov po nablyudeniyam stantsiy seti Gidrometsluzhby za 1957 i 1958 gg (Visible Frequency of Appearance of Noctilucent Clouds according to the Observations of the Stations of the Hydrometeorological Service for 1957 and 1958), in: Issledovaniya serebristykh oblakov (Studies of Noctilucent Clouds), No. 1. Leningrad State University, 1960.
3. Khovostikov, I.A.: Serebristyye oblaka i stroyeniye atmosfery (Noctilucent Clouds and the Structure of the Atmosphere), in: Trudy Soveschaniya po serebristym oblakam (Works of a Conference on Noctilucent Clouds), Vol. III. Tallin, 1962.
4. Grishin, N.I.: Izucheniye dvizheniy serebristykh oblakov (Study of the Movements of Noctilucent Clouds). Byull. VAGO, No. 21, 1958.
5. Grishin, N.I,: Volnovyye dvizheniya i meteorologicheskiye usloviya poyavleniya serebristykh oblakov (Wave Movements and Meteorological Conditions in the Appearance of Noctilucent Clouds), in: Nekotoryye problemy meteorologii (Some Problems of Meteorology), No. 1. Izdat. Akad. Nauk S.S.S.R., 1960.
6. Grishin, N.I.: K voprosu o meteorologicheskikh usloviyakh poyavleniya serebristykh oblakov (The Problem of the Meteorological Conditions for the Appearance of Noctilucent Clouds), in: Trudy VI Soveshchaniya po serebristym oblakam (Works of the Sixth Conference on Noctilucent Clouds). Riga, 1961.
7. Batten, E.: Wind Systems in the Mesosphere and Lower Ionosphere. J. Meteorol., Vol. 18, No. 3, 1961.
8. Grishin, N.I.: Meteorologicheskiye usloviya poyavleniya serebristykh oblakov (Meteorological Conditions for the Appearance of Noctilucent Clouds), Byull. VAGP, No. 15, 1954.

9. Charney, I. and p. Drazin: Propagation of Planetary-Scale Disturbances from the Lower into the Upper Atmosphere. J. Geophys. Res., Vol. 66, No. 1, 1961.
10. Hines, C.O.: Internal Atmospheric Gravity Waves at Ionospheric Heights. Canad. J. Phys., Vol. 36, No. 11, 1960.
11. Hines, C.O.: The Upper Atmosphere in Motion. Quart. J. Roy. Meteorol. Soc., Vol. 89, No. 379, 1963.
12. Gossard, P.: Vertical Flux of Energy into the Lower Atmosphere /77 from Internal Gravity Waves Generated in the Troposphere. J. Geophys. Res., Vol. 67, No. 2, 1962.
13. Yakkia, L.: Vliyaniye Solntsa na uskoreniye iskusstvennykh sputnikov Zemli (The Effect of the Sun on the Acceleration of Artificial Earth Satellites), in: Isslodovaniya verkhney atmosfery s pomoshch'yu raket i sputnikov (Studying the Upper Atmosphere with the Aid of Rockets and Satellites). Foreign Literature Publishing House, 1961.
14. Kallmann, H.: Daytime and Nighttime Atmospheric Properties Derived from Rocket and Satellite Observations. J. Geophys. Res., Vol. 66, No. 3, 1961.
15. Anderson, A.: A. Simple Model for Atmospheric Density Variations from 200 to 700 km. J. Atmos. Sci., Vol. 19, No. 3, 1962.
16. Rubashev, B.M.: O nagrevanii verkhnikh sloyev atmosfery Zemli vo vremya magnitnykh bur' (The Heating of the Upper Layers in the Earth's Atmosphere during Magnetic Storms). Izvest. Glavnoy Astron. Observ., Vol. 20, No. 6 (159), 1958.
17. Batrakov, Yu.V.: Obrabotka nablyudeniy tret'yego sovetskogo iskusstvennogo sputnika Zemli v Institute teoreticheskoy astronomii AN SSSR (An Analysis of the Observations of the Third Soviet Artificial Earth Satellite at the Institute of Theoretical Astronomy of the Academy of Sciences of the U.S.S.R.). Byull. Instit. Teoret. Astron., Vol. 7, No. 10, 1960.
18. Paetzold, H. : Zustand und Variationen der hohen Atmosphäre nach Satelliten Beobachtungen (State and Variations of the Upper Atmosphere on the Basis of Satellite Observations), Raketentechnik und Raumfahrtforschung, Vol. 5, No. 4,1961.
19. Paetzold, H.: Corpuscular Heating of the Upper Atmosphere. J. Geophys. Res., Vol. 67, No. 7, 1962.
20. L. Jacchia. Satellite drag during the events of November 1960. - Space Res II. Amsterdam, 1961
21. Groves. Correlation of upper atmosphere air density with geomagnetic activity, November 1960. - Space Res. II, 1961.
22. R. Jastrow. Geophysical effects of the trapped particle layer. - Space Res., 1, 1960.
23. J. Blythe. The scientific uses of Earth satellites. - Radio Techn. and Space Res. Oxford, 1961.
24. R. Jastrow, Rossi. Results of experiments in space. Sci. in Space, No. 4, 1961.

25. L. Berkofsky, R. Schapiro. A dynamical model for investigations of the downward transfer of energy introduced by upper atmosphere heating. - Planet. and Space Sci., 7, N 1, 1961.
26. Lebedeva, I.I.: Nekotoryye sluchai poyavleniya yarkikh serebristykh oblakov letom 1955 g (Some Cases of an Appearance of Bright Noctilucent Clouds during the Summer of 1955), in: Issledovaniya serebristykh oblakov (Studies of Noctilucent Clouds), No. 1. Leningrad State University, 1960.
27. Parshin, I.A.: Absolyutnaya fotometriya sumerechnogo neba i serebristykh oblakov (Absolute Photometry of the Twilight Sky and Noctilucent Clouds), in: Issledovaniya serebristykh oblakov (Studies of Noctilucent Clouds), No. 1. Leningrad State University, 1960.
28. Khvostikov, I.A.: Serebristyye Oblaka i stroyeniye stratosfery (Noctilucent Clouds and the Structure of the Stratosphere), in: Sbornik Pamyati S.I. Vavilova (Collection Dedicated to S.I. Vavilov). Izdat. Akad. Nauk S.S.S.R., 1952.
29. Bronshten, V.A.: O prirode serebristykh oblakov (The Nature of Noctilucent Clouds), in: Trudy soveshchaniya po serebristym oblakam. Works of a Conference on Noctilucent Clouds), Vol. II, Riga, 1961.
30. Khvostikov, I.A.: Proiskhozhdeniye serebristykh oblakov i temperatura atmosfery v mezopauze (The Origin of Noctilucent Clouds and the Temperature of the Atmosphere in the Mesopause), in: Trudy soveshchaniya po serebristym oblakam (Works of a Conference on Noctilucent Clouds), Vol. II Riga, 1961.
31. Khvostikov, I.A.: Serebristyye oblaka i stroyeniye atmosfery (Noctilucent Clouds and the Structure of the Atmosphere), in: Trudy soveshchaniya po serebristym oblakam (Works of a Conference on Noctilucent Clouds), Vol. III, Tallin, 1962.
32. Villmann, C.I.: Nekotoryye rezul'taty izucheniya prirody serebristykh oblakov (Some Results of a Study of the Nature of Noctilucent Clouds). Dissertation. Tartu, 1963.
33. T. Hesstvedt. On the possibility of the cloud formation at the mesopause. - Tellus, 14,3, 1962.
34. Kondrat'yev, K.Ya.: Meteorologicheskiye issledoveniya s pomoshch'yu raket i sputnikov (Meteorological Studies with the Aid of Rockets and Satellites), Chap. V. "Gidrometeoizdat", 1962.
35. A. Maxwell. Turbulence in the upper atmosphere. - Phil. Mag., 45, N 371, 1954.
36. I.-E., Blammont. Turbulence in the atmospheric motions between 90 and 130 km of altitude. - Planet. and Space Sci., 10, 1963.
37. Borovikov, A.M., et al.: Fizika oblakov (The Physics of Clouds), Chap. VIII. Leningrad, "Gidrometeoizdat", 1961. /78
38. Nicolet, M.: Dynamic Effects in the High Atmosphere. The Earth as a Planet, ed. G. Kuiper. Chicago, 1954.

39. Witt, G.: Height, Structure and Displacement of Noctilucent Clouds. Tellus, Vol. 14, No. 1, 1962.
40. Matveyev, L.T.: Usloviya obrazovaniya i evolyutsii oblakov pod vliyaniyem vertikal'nyk tokov i turbulentnogo obmena (The Conditions for the Formation and Evolution of Clouds by the Effect of Vertical Currents and Turbulent Mixing). Invest. Akad. Nauk S.S.S.R., seriya geofiz., No. 1, 1961.
41. Klubovich, K.V.: Obrazovaniye oblakov v odnorodnoy vozdushnoy masse (The Formation of Clouds in a Homogeneous Air Mass). Vestnik MGU, seriya III. Fizika, astronomiya, 1963.
42. Gutman, L.N.: K teorii kuchevoy oblachnosti (The Theory of Cumulus Clouds). Invest. Akad. Nauk S.S.S.R., seriya geofiz., No. 7, 1961.
43. Gutman, L.N.: Statsionarnaya osesimmetrichnaya model' kuchevogo oblaka (Stationary Axisymmetric Model of a Cumulus Cloud). Doklady Akad. Nauk S.S.S.R., Vol. 150, No. 1, 1963.
44. Gutman, L.N.: Primeneniye metoda dlinnykh voln k zadache obtekaniya gor (Applying the Method of Long Waves to the Streamline Flow of Mountains). Doklady Akad. Nauk S.S.S.R., Vol. 115, No. 3, 1957.
45. Obayashi, T.: Upper Atmosphere Disturbance due to High Atmosphere Nuclear Explosions. Planet. and Space Sci., Vol. 10, 1963.
46. Macdonald, G.: Circulation and Tides in the High Atmosphere. Planet. and Space Sci., Vol. 10, 1963.
47. Morse, F., and G. Feshbach: Metody teoreticheskoy fiziki (Methods of Theoretical Physics), Vol. II, Chap. II. Foreign Literature Publishing House, 1958.
48. Blinova, Ye.N.: Ob opredelenii skorosti dvizheniya lozhbin iz nelineynogo uravneniya dlya vikhrya (Determing the Rate of Motion of the Troughs form a Nonlinear Vorticity Equation). Prikladnaya Matematika i Mekhanika, No. 5-6, 1956.
49. Dobryshman, YeM.: O primerakh tochnykh resheniy nelineynykh prognosticheskiky uravneniy (Examples of Precise Solutions to Nonlinear Probability Equations). Invest. Akad. Nauk S.S.S.R., seriya geofiz., No. 2, 1961.
50. Kuo, H.L.: Finite-Amplitude Three-Dimensional Harmonic Waves on the Spherical Earth. J. Meteorol., Vol. 16, No. 5, 1959.
51. Yih, C.S.: Exact Solutions for Steady Two-Dimensional Flows of a Stratified Fluid. J. Fluid Mech., Vol. 9, No. 2, 1960.
52. Aihara, M.: Time - Dependent Behaviours of Parallel Flows in a Non-Vergent Barotropic Atmosphere. J. Meteorol. Soc. Japan, Series II, Vol. 39, No. 4, 1961.
53. Titchmarch; Razlozheniya po sobstvennym funktsiyam, svyazannyye s differentsial'nymi uravneniyami vtorogo poryadka (Arrangements by Inherent Functions Related to Differential Equations of the Second Order), Vol. II, Chap. XI. Foreign Literature Publishing House, 1961.
54. Platzman, G.W.: A Solution of the Nonlinear Vorticity Equation. The Atmosphere and the Sea in Motion. New York, 1959.

55. Soberman, R.K.: Noctilucent Clouds. Sci. American, Vol. 208, No. 6, June, 1963.
56. Haurwitz, B.: Wave Formation in Noctilucent Clouds. Planet. and Space Sci., Vol. 5, No. 2, 1961.
57. Novozhikov, N.I.: Ob uchete volnovykh dvizheniy v serebristykh oblakakh pri opredelenii struktury mezopauzy (Considering the Wave Movements in Noctilucent Clouds in Determining the Structure of the Mesopause), in: Trudy Soveshchaniya po serebristym oblakam, III (Works of the Third Conference on Noctilucent Clouds). Tallin, 1962.
58. Scorer, R.S.: Theory of Waves in the Lee of Mountains, I. Quart. J. Roy. Meteorol. Soc., Vol. 75, No. 323, 1949.
59. Kochansky, A.: Circulation and Temperature at a Height of 70 to 100 km. J. Geophys. Res., Vol. 68, No. 1, 1963.
60. Trubnikov, B.N.: K teorii orograficheskikh chechevitseobraznkh oblakov (The Theory of Orographic Lenticular Clouds). Vestnik MGU, No. 5, Seriya III. Fizika, astronomiya, 1961.
61. Hesstvedt, E.: A Two-Dimensional Model of Mother-of-Pearl Clouds. Tellus, Vol. 14, No. 3, 1962.

# SOME REMARKS ON THE RELATIONSHIP BETWEEN THE APPEARANCES OF NOCTILUCENT CLOUDS AND THE REINFORCEMENT OF THE ZONALITY OF ATMOSPHERIC CURRENTS ON THE EARTH AND THE SUNSPOT ACTIVITY

A.Ya. Bezrukova

*ABSTRACT: The author analyzes the number of days when noctilucent clouds appeared and the number of days when atmospheric currents were in definite zones. The results indicated that these changes in the external formations in the Earth's atmosphere have a cyclic nature very similar to that of the 11-year cycle of sunspot activity.*

In the Works of the Sixth Conference on Noctilucent Clouds, the article written by I.S. Astapovich [1] gives a survey of the observations of noctilucent clouds in Russia and the USSR from 1885 to 1944. Considering that noctilucent clouds are external formations in the atmosphere of our planet, it seems of interest to use this survey in order to compare it with the 11-year cycle of sunspot activity. /79

Most of the observations of noctilucent clouds were conducted after 1917. Therefore, the number of their appearances was calculated in the survey of noctilucent clouds for the period from 1920 to 1944, i.e., mainly for Cycles No. 16 and 17 of the solar activity. In this case, all the observations of noctilucent clouds on one night were considered as one appearance.

It was also noted that the maximum recurrences of noctilucent clouds were observed during the months of June, July, and August (in rare cases, single appearances were observed in April and May), i.e., during those months when the heliographic latitude of the center of the Earth's disk is positive (the northern hemisphere of the Sun is turned toward the Earth).

Various geophysical phenomena are usually compared with the Wolf numbers, which are calculated for the entire solar disk. These numbers do not consider the fact that the Earth is oriented differently in respect to the solar equator during the course of a year, while the sunspot process does not occur identically in both hemispheres of the Sun.

In order to compare the appearances of noctilucent clouds with the sunspot activity, we used the solar index for a mean square during the time of existence of the group. From 1920 to

1960, the sum of the mean squares was calculated according to Greenwich data [2] for each year.

For Cycle No. 10, the sum of the average areas was given on the basis of a preliminary analysis of the data from observations of only one station, the Gorniy station of the Main Astronomical Observatory of the Academy of Sciences of the USSR.

Considering the orientation of the Earth relative to the solar equator, we must compare the recurrences of noctilucent clouds from the month of June to the area of groups of sunspots in the northern hemisphere of the Sun.

We should remember that the Earth passes through points on its /80 orbit during rotation around the Sun, toward which both the northern and the southern hemispheres of the Sun are turned. The heliographic latitude of the Earth's disk reaches 7° twice a year, and zero twice a year. This is a consequence of the fact that the planes of the Earth's orbit and the solar equator do not coincide, but form an angle of 7°. In September and March, the heliographic latitude of the Earth's disk is greatest, and we can see the north pole of the Sun in September, and the south pole in March. On December 6 and June 4, the axis of the Sun (from the Earth's orbit) is perpendicular to the line of sight, and the heliographic latitude of the center of the Earth's disk is equal to zero during this time. Having considered this circumstance, we excluded from the survey those appearances of noctilucent clouds which occurred during April and May, when the heliographic latitude of the center of the Earth's disk was negative. There were only five such appearances from 1920 to 1944 (one in 1926, one in 1934, one in 1937, and two in 1938). The remaining appearances of noctilucent clouds were related in time to a positive heliographic latitude of the center of the Earth's disk, and thus were included in our examination (see the figure).

We can see from the figure that the two-peak curve for the change in the area of groups of sunspots in the northern hemisphere of the Sun also corresponds to the two-peak curve for the change in the number of appearances of noctilucent clouds in Cycle No. 16. In Cycle No. 17, the curve for the change in the areas of the groups of sunspots had one peak. The single-peak curve, with a maximum in 1937, is also reflected in the curve for the appearances of noctilucent clouds. The level of activity of Cycle No. 17 is higher than that for Cycle No. 16, so that the number of appearances of noctilucent clouds in Cycle No. 17 is greater than in the preceding cycle (No. 16).

There were isolated reports of the appearance of noctilucent clouds [3] during the period from 1950 to 1959. Let us analyze the appearances of noctilucent clouds during Cycle No. 19 of solar activity. In the Information Bulletin of the IGY [4], an article written by N.I. Grishin showed a table for the appearances of noctilucent clouds from 1950 to 1957. The author stipulated that the data for 1957 could not be trusted, since the large number of appearances of nocticlucent clouds during 1957 could be explained by the organization of a large network of observational stations during the IGY. Moreover, the recurrence of noctilucent clouds during 1957 was considered by experienced observers to be on the same level as that for 1952-1956. According to C.I. Villmann [5], the station at Tallin recorded eight appearances of noctilucent clouds in 1957, and four in 1958. As V.Yu. Skul'skiy [6] has noted, the number of appearances of noctilucent clouds in the Urals during 1957 was greater than that in 1958. In 1959, noctilucent clouds were observed which were significant in intensity, dimensions, and duration [7]; according to the data of C.I. Villmann [8], there were 13 appearances of noctilucent clouds over the Estonian S.S.R. M.A. Dirikis [9] has described the large number of noctilucent clouds observed in 1959 over Riga. Thus, the year 1959 was significant for the large values of different characteristics of noctilucent clouds. As we can see from the figure, 1959 was the year of a maximum in the 11-year cycle in the northern hemisphere of the Sun, and the time of the greatest values for the area of groups of sunspots (since 1874). The exceptionally high level of activity of the 11-year cycle (No. 19) of the solar activity was reflected in the number of appearances of noctilucent clouds during the period from 1954 to 1959. /81

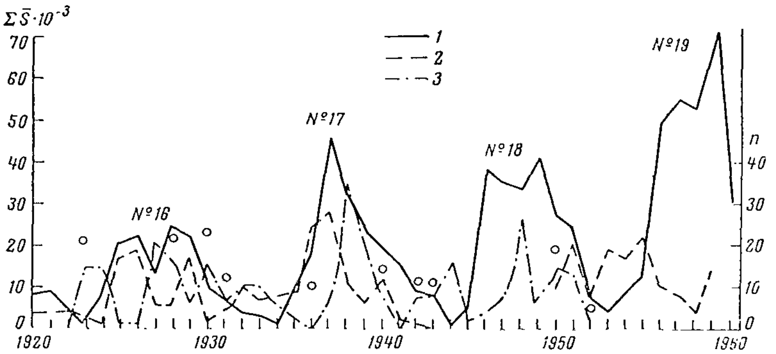


Fig. 1. Comparison of the Number of Appearances of Noctilucent Clouds, Areas of Sunspots, and Number of Days with Zonal Circulation for 1920-1960. (1) Cyclic Change in the Areas of Groups of Sunspots in the Northern Hemisphere of the Sun; (2) Number of Appearances of Noctilucent Clouds; (3) Number of Days with Zonal Circulation during September-November. The Abscissa shows the Years, and the Ordinate shows the Sum of Average Areas for Groups of Sunspots ($\Sigma S$) and the Number of Appearances of Noctilucent Clouds ($n$) for Each Year.

I would like to mention one more interesting increase in the frequency of appearance of noctilucent clouds during 1950-1951, which can also confirm the relationship between solar activity and noctilucent clouds. In the survey of the appearances of noctilucent clouds [4], the number 10 is given for 1950, and the number 21 is given for 1951. A study of the fluctuations in the areas of groups of sunspots with the revolution of the Sun according to Greenwich data [10] shows that there were strong fluctuations in the solar activity in the northern hemisphere of the Sun during 1950 and 1951; long-lasting spots which were visible to the naked eye were included in this phenomenon [11]. One of the groups of spots in 1951 lasted for five solar revolutions, and the average area during the time it lasted was 3743 millionths of the hemi- /82
sphere. According to the heliographic latitude, this group extended from 13.5 to 5°, and the Earth was often submerged in the radiation from this group during its rotation around the Sun.

In the oscillations of the number of appearances of noctilucent clouds, there were intensifications in the minima (or very near the minima) in the 11-year cycle, as well as intracyclic maxima. If we were to plot even incomplete data on the appearances of noctilucent clouds for 1950-1959 on the figure, we would see that, in addition to the intracyclic maxima, there was an increase in the frequency of appearances of noctilucent clouds at the beginning of the twenties and the fifties, as well as in 1932. There were similar intensifications in other geophysical phenomena, including the zonality of the atmospheric currents [12], i.e., the west-to-east transfer of air masses on our planet. Let us compare the number of appearances of noctilucent clouds to the intensification of the zonality of atmospheric currents at middle latitudes of the Earth for the period of time in question. We will use B.L. Dzerdzeyevskiy's classification of the atmospheric circulation [13] for this purpose, and we will calculate the number of days when the first type of atmospheric circulation (intensification of the west-to-east transfer of air masses) was observed during the period of a positive heliographic latitude for the center of the Earth's disk. The first circulation mechanism is observed primarily during the autumn and early winter. It is not observed earlier than September; therefore, we must calculate the number of days with this type of atmospheric circulation during the period from September to November, i.e., when the northern hemisphere of the Sun is turned toward the Earth. Actually, we can include four months (to December, inclusively), since the possibility of a lag in the process has not been excluded.

The dashed lines in Figure 1 show the change in the number of days with a zonal circulation during the period from September to November. The small circles show the values obtained from calculations which included December. The curve for the change in the number of days with zonal circulation during the 11-year solar cycle has the same shape as the curve for the change in the number of appearances of noctilucent clouds. It has two peaks in Cycle No. 16, and one peak in Cycle No. 17; however, the maxima of the zonal atmospheric circulation lag one or two years behind the maxima of the solar cycles and the maxima of the number of appearances of noctilucent clouds.

During 1950-1951, both maxima coincide (for the appearances of noctilucent clouds and for the intensification of the west-to-east transfer of air masses); this is seen even more clearly when the number of days with atmospheric circulation includes the period from September to December.

On the basis of an analysis of the number of days when nocti- /83
lucent clouds appeared, and the number of days when the atmospheric currents on our planet were in definite zones, we see that the change in the number of external formations in the Earth's atmosphere (noctilucent clouds and days with zonal circulation, i.e., processes in the lower layers of the atmosphere) has a cyclic nature which repeats the single-peak and two-peak characteristics of the development of 11-year solar cycles. It is true that the development of the latter lags somewhat behind the former and (correspondingly) behind the development of the sunspot activity as well.

In relation to this study, it is relevant to mention the cyclic change in the brightness of the night sky and the lag of the maximum in the curve for the brightness of the green line, according to the observations at Thurling (England), by one year, in comparison to the maximum for the curve for the area of sunspots [14].

## REFERENCES


1. Astapovich, I.S.: Trudy VI soveshchaniya po serebristym oblakam (Works of the Sixth Conference on Noctilucent Clouds). Riga, 1961.
2. Greenwich Photo-Heliographic Results. London, 1917-1944.
3. Vestine, E.H.: J. Roy. Astron. Soc. Can., Vol. 28, pp. 249-303, 1964.
4. Grishin, N.I.: Informatsionnyy byulleten' MGG (Information Bulletin of the IGY), No. 5, 1958.
5. Villmann, C.I.: Trudy soveshchaniya po serebristym oblakam (Works of a Conference on Noctilucent Clouds). Tartu, December 12-14, 1958. Tartu, 1959.
6. Skul'skiy, V.Yu.: Trudy soveshchaniya po serebristym oblakam (Works of a Conference on Noctilucent Clouds). Tartu, December 12-14, 1958. Tartu, 1959.
7. Sharonov, V.V.: Trudy VI soveshchaniya po serebristym oblakam (Works of the Sixth Conference on Noctilucent Clouds). Riga, 1961.
8. Villmann, C.I.: Trudy VI soveshchaniya po serebristym oblakam (Works of the Sixth Conference on Noctilucent Clouds). Riga, 1961.

9. Dirikis, M.A.: Trudy VI soveshchaniya po serebristym oblakam (Works of the Sixth Conference on Noctilucent Clouds). Riga, 1961.
10. Bezrukova, A.Ya.: Byull. Komissii po Issledovaniyu Solntsa (Bulletin of the Solar Research Commission), No. 10, 1954.
11. Sunspot and Geomagnetic Storm Data Derived from Greenwich Observations. London, 1955.
12. Bezrukova, A.Ya.: Solnechnyye dannyye (Solar Data), No. 7, 1960.
13. Dzerdzeyevskiy, B.L., V.M. Kurganskaya and Z.M. Vitvitskaya: Tipizatsiya tsirkulyatsionnykh mekhanizmov v severnom polusharii (Classification of the Circulation Mechanisms in the Northern Hemisphere). Moscow-Leningrad, "Gidrometizdat", 1946.
14. Cherednichenko, V.I.: Astronomicheskiy sbornik (Astronomical Handbook), Vol. 3-4. Izdat. "L'vovskogo universiteta", 1960, p. 64.

# THE RESULTS OF PHOTOMETRIC OBSERVATIONS OF NOCTILUCENT CLOUDS

C.I. Villmann

*ABSTRACT: The results of photometric observations of noctilucent clouds are analyzed and interpreted in this article. It is shown that the absolute brightness of noctilucent clouds can vary within a rather broad range. The author discusses the principal reasons for such a phenomenon on the basis of the ice (condensation), dust, and compromise theories concerning the formation of noctilucent clouds.*

## 1. Introduction

The principal task of photometric observations of noctilucent clouds in our program was to obtain the albedo of the medium at various points of the field being observed. By the albedo of the medium, we mean the total energy generated by the medium on a unit surface in a unit of time (in terms of energy percentage) and incident on a unit surface (from an external light source) in a unit time. In addition to analyzing the data obtained from polarimetric studies concerning the dimensions and reflectivity of the particles forming noctilucent clouds [1,2], we have also attempted to evaluate the concentration of the matter in noctilucent clouds and the thickness of the layer at various points of the cloud field, and to determine the curve for the light diffusion of noctilucent clouds. /84

We analyzed photographs of noctilucent clouds made with a three-lens camera which was specially designed for photometric, polarimetric and colorimetric studies of plane celestial objectives [3]. The methods for the photometric observation, calibration, and standardization of the photographs were described in [3].

We used three occurrences of noctilucent clouds (July 15-16, 1959, July 8-9 and August 7-8, 1961) to determine the brightness of single details in the cloud field, and one occurrence (July 30-31, 1959) to determine the characteristic curve of the light diffusion from particles in the noctilucent clouds.

The photometric standardization of the brightness of the measured elements was made according to the following:

(1) according to the Sun, for the occurrence on July 15-16, 1959 (the standardized photographs were obtained in the morning immediately after the noctilucent clouds were photographed);

(2) according to the extrafocal image of Capella, for July 8-9, 1961 (this was found during the photographing of noctilucent clouds in the immediate vicinity of the latter);

(3) according to Venus, for the occurrence on August 7-8, 1961 (the planet appeared together with the noctilucent clouds).

## 2. Determining the Brightness of Elements and the Concentration of Particles in the Cloud Field

Let $B_0$ be the brightness of the noctilucent clouds; in this case, we find the following expression: /85

$$B_0 = r_{sc} \frac{b_0 - b_{sk}}{b_{stan}} \tag{1}$$

where $b_0$ is the measured total brightness for a certain point in the field; $b_{sk}$ is the brightness of the twilight sky at the same point, when there are no noctilucent clouds; $b_{stan}$ is the brightness of a standard screen at the moment when the elevation of the Sun above the horizon is equal to the height of the measured point in the cloud; $r_{sc}$ is the coefficient of reflection of the screen. If we do not know $r_{sc}$, the unit brightness which must be included in $B_0$ is the brightness of an absolutely white screen located at right angles to the solar rays at the limit of the Earth's atmosphere. In this case, it is assumed that the transparency of the Earth's atmosphere is the same during observations of the noctilucent clouds, the twilight sky, and the sunlight.

This method was used in analyzing the observations of July 15-16, 1959.

The photographs which contained images of Capella and Venus (for July 8-9 and August 7-8, 1961) were analyzed by the standardization method according to the extrafocal images of the stars. The brightness of the elements in the cloud field was found according to the following formula:

$$\mathfrak{M} = m + 2{,}5 \log \frac{\pi}{4} d''^2 - 2{,}5 \log \frac{b_0}{b_{st}} \tag{2}$$

where $\mathfrak{M}$ is the brightness of the element in the cloud in stellar magnitudes per square second of arc; $m$ is the stellar brightness;

$d''$ is the diameter of the extrafocal image of the star per second of arc; $b_0/b_{st}$ is the ratio between the brightness of the detail in the cloud and the effective brightness of the disk of the star obtained by using the characteristic curve.

The advantage of this method of standardization for photometry of noctilucent clouds is the following: having photographed the star and the noctilucent clouds at the same moment, and having selected for the measurements those points in the cloud field whose zenith distance is equal to the zenith distance of the star, we can exclude the effect of atmospheric extinction from the observations.

In addition to determining the brightness of single details in the cloud field, we also found the value for the contrast of the brightness of the cloud against the background of the sky. It is well known that the latter determines the visibility of the cloud; it is found by the following formula:

$$K = \frac{b_0 - b_{sk}}{b_0} \quad (3)$$

where $b_0$ and $b_{sk}$ have the same meaning as in (1). Since it is impossible to measure $b_{sk}$ directly, because of the details in the cloud, we used the value $b$, as the half-sum of the brightnesses for points in a pure, cloudless sky located above ($b_{sk1}$) and below ($b_{sk2}$) the observed detail in the noctilucent clouds. /86

TABLE 1

| [illegible] | Photographed Objective | Date | Time | Exposure Time | Relative Aperture | Filter | Solar Coordinates $A$ | Solar Coordinates $z$ | Comment |
|---|---|---|---|---|---|---|---|---|---|
| 1[illegible] | Noctilucent Cloud | [illegible] | [illegible] | [illegible] | 1:22 | ZhS-17 | 187°53' | [illegible]8°47' | |
| [illegible]7 | Twilight Sky | 17 [illegible] | [illegible] | 30 | 1:22 | ZhS-17 | 187 32 | [illegible] 39 | |
| [illegible]-144 | Sun | [illegible] | [illegible] | [illegible] | 1:22 | ZhS-17 | - | [illegible]7 00-100 00 | |
| 42 | Noctilucent Clouds | [illegible] | [illegible] | 30 | 1:22 | - | 186 35 | 98 07 | Lower & Upper Photos Extra-focal |
| 137 | Same | 8 Aug 61 | [illegible]2 44 05 | 30 | 1:22 | - | 220 43 | 96 53 | Same |

Table 1 gives the conditions under which the photographs were made. The average exposure time is given in true solar time.

We constructed a Bouguer line according to the observations of the Sun on July 16, 1950 (Fig. 1). Although the Sun was photographed from the moment of sunrise to $z = 65°$ (with an atmospheric mass $M_z$ from 27.0 to 2.6 according to the Bemporad table), we could only use the observations for $M_z$ = 7.8-5.6 for the standardization. This was caused by the fact that when $M_z$ was greater than 7.8, the Sun was seen through an atmospheric haze, and the photographs obtained for $M_z$<5.6 were overexposed because the coefficient of transparency of the filter was too great ($r_{sc}$=3.43·10$^{-4}$).

The results of the calculations for the brightness and contrast of details of the noctilucent clouds are shown in Table 2.

As we can see from Table 2, the brightness of the noctilucent clouds observed on July 8-9 and August 7-8, 1961 was lower (by several orders of magnitude) than that of the clouds observed on July 15-16, 1959. Judging by the comments in the log for the observations, the noctilucent clouds of July 15-16, 1959 were exceptionally bright, while the details in the cloud fields observed on July 8-9 and August 7-8, 1961 were faint or moderately bright. This is also indicated by the values for the contrast $K$ which we calculated. Moreover, we should consider the fact that the angles of scatter for the measured details in the cloud field varied on the different dates. Thus, for example, the angle of scatter for /87
the points whose brightness was determined on July 8-9, 1961 were almost equal to 90°, while they were only from 21 to 29° for July 15-16, 1959. Therefore, it is very probable that the curve for the scatter of the particles forming the noctilucent clouds has a more or less extended appearance. In this case, we can consider that the principal beam of radiation on July 15-16, 1959 was directed toward the sensitive element, while only a small part of the light (the part which was diffused by particles of the noctilucent clouds at an angle of 90°) was directed toward the sensitive element on July 8-9, 1961. Although the angles of scatter of the measured points in the noctilucent clouds of August 7-8, 1961 were also small (from 19 to 26°), i.e., the principal beam of scattered radiation was directed toward the sensitive element, the brightness of the details in this cloud field was also moderate. In all probability, the concentration of cloud particles was less in this case than on July 15-16, 1959.

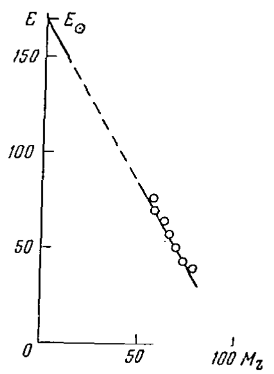

Fig. 1. Bouguer Line.

The intensity of the scattered light produced by the particles in noctilucent clouds depends on the dimensions, the quantity per unit volume, and the physical nature of individual scattered particles. In general, the greater the dimensions of the particle, the more strongly it scatters the light. However, when the total mass of the scattered matter has been produced previously (as can be the case with noctilucent clouds), the increase in the dimensions of the particles leads to a reduction of their number, which cannot be compensated under certain conditions by the increasing "scattering factor". Thus, for example, if $r \gg \lambda$ ($r$ is the radius of the

## TABLE 2

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| Date | Coordinates A | Coordinates z | $\vartheta$ | $B_0$ | $M$ | $k$ | Measured Detail |
|---|---|---|---|---|---|---|---|
| 15—16 Jul 1959 | 209°31′ | 78°24′ | 21°22′ | $1{,}1\cdot10^{-6}$ | — | 0,21 | Veil |
| Same | 209 31 | 77 33 | 21 28 | $2{,}7\cdot10^{-6}$ | — | 0,50 | Faint Crest |
| » » | 211 15 | 73 28 | 23 58 | $1{,}9\cdot10^{-6}$ | — | 0,60 | Same |
| » » | 212 06 | 75 44 | 24 15 | $9{,}4\cdot10^{-6}$ | — | 0,70 | Bright Crest |
| » » | 216 08 | 75 45 | 28 06 | $10{,}0\cdot10^{-6}$ | — | 0,70 | Eddy |
| » » | 216 49 | 80 52 | 28 28 | $17{,}0\cdot10^{-6}$ | — | 0,60 | Eddy Center |
| » » | 216 49 | 79 41 | 28 29 | $12{,}0\cdot10^{-6}$ | — | 0,59 | Eddy Edge |
| » » | 216 49 | 76 23 | 28 40 | $2{,}4\cdot10^{-6}$ | — | 0,59 | Faint Crest |
| » » | 216 55 | 81 17 | 28 16 | $16{,}0\cdot10^{-6}$ | — | 0,56 | Eddy |
| » » | 217 03 | 80 51 | 28 42 | $28{,}0\cdot10^{-6}$ | — | 0,61 | Eddy Center |
| » » | 217 03 | 79 28 | 28 43 | $14{,}0\cdot10^{-6}$ | — | 0,46 | Same |
| 8—9 Jul 1961 | 267 20 | 43 45 | 89 32 | $2{,}4\cdot10^{-11}$ | 16,3 | 0,02 | Band |
| Same | 267 39 | 43 01 | 89 54 | $8{,}7\cdot10^{-11}$ | 14,9 | 0,06 | » |
| » » | 266 53 | 43 55 | 89 12 | $5{,}5\cdot10^{-11}$ | 15,4 | 0,04 | » |
| » » | 266 55 | 43 09 | 89 23 | $9{,}6\cdot10^{-11}$ | 14,8 | 0,06 | » |
| » » | 265 52 | 41 45 | 81 09 | $6{,}0\cdot10^{-11}$ | 15,3 | 0,04 | » |
| » » | 262 30 | 41 03 | 87 02 | $8{,}7\cdot10^{-11}$ | 14,9 | 0,06 | » |
| » » | 261 13 | 41 23 | 86 08 | $2{,}5\cdot10^{-11}$ | 16,0 | 0,02 | » |
| 7—8. Aug 1961 | 238 49 | 75 15 | 19 25 | $2{,}4\cdot10^{-9}$ | 11,3 | 0,10 | » |
| Same | 239 12 | 75 15 | 19 46 | $2{,}2\cdot10^{-9}$ | 11,4 | 0,08 | » |
| » » | 238 15 | 75 15 | 18 55 | $2{,}6\cdot10^{-9}$ | 11,2 | 0,12 | » |
| » » | 238 15 | 75 51 | 18 42 | $2{,}4\cdot10^{-9}$ | 11,3 | 0,10 | » |
| » » | 238 15 | 75 19 | 18 54 | $2{,}9\cdot10^{-9}$ | 11,1 | 0,12 | » |
| » » | 238 15 | 75 53 | 18 41 | $2{,}6\cdot10^{-9}$ | 11,2 | 0,08 | » |
| » » | 238 53 | 75 15 | 19 29 | $3{,}2\cdot10^{-9}$ | 11,0 | 0,12 | » |
| » » | 245 05 | 78 11 | 24 32 | $2{,}6\cdot10^{-9}$ | 11,2 | 0,09 | » |
| » » | 245 05 | 77 56 | 24 34 | $2{,}4\cdot10^{-9}$ | 11,3 | 0,06 | » |
| » » | 245 05 | 77 54 | 24 35 | $2{,}6\cdot10^{-9}$ | 11,2 | 0,08 | » |
| » » | 245 11 | 77 53 | 24 41 | $2{,}4\cdot10^{-9}$ | 11,3 | 0,06 | » |
| » » | 245 11 | 77 37 | 24 44 | $2{,}9\cdot10^{-9}$ | 11,1 | 0,10 | » |
| » » | 246 50 | 78 19 | 26 12 | $2{,}6\cdot10^{-9}$ | 11,2 | 0,11 | » |

Note: $\theta$ signifies the angle of scatter, $B_0$ is expressed in solar units and can be used as the apparent albedo of the medium ($A_B$) of the clouds; $M$ signifies the brightness of the detail in the cloud field in stellar magnitudes per square second of arc; $K$ is the brightness contrast between the detail in the cloud and the background of the sky; $A$ and $z$ are the azimuth and the zenith distances of the measured detail in the field, respectively.

particles, $\lambda$ is the length of the light wave) for particles with $r \approx 10^{-5}$-$10^{-4}$ cm, i.e., for the particles which we found in polarimetric studies of noctilucent clouds [1,2], the scattering capacity increases with an increase of $r$ in proportion to $r^2$, while the number of particles increases in proportion to $r^3$. Therefore, the total intensity of the scattered light produced by the particles decreases when $r$ increases.

Knowing the apparent albedo of the medium, we can evaluate the concentration and volumetric density of the particles in noctilucent clouds.

In order to calculate the concentrations, we introduced the following formula:

$$\chi = \frac{A_{ap}}{A^*} \cdot \frac{1}{\pi r^2 d} \frac{1}{\sec\left[\arcsin\left(\frac{R}{R+H}\sin z\right)\right]}, \qquad (4)$$

where $A_{ap}$ is the apparent albedo of the medium; $A^*$ is the albedo of single particles; $d$ is the vertical thickness of the layer of noctilucent clouds;

$R$ is the radius of the Earth; $H$ is the height of the noctilucent clouds from the ground; $z$ is the zenith distance of the point in the cloud field; $r$ is the radius of the particles. /89

The volumetric density of the noctilucent clouds was calculated according to the following formula:

$$\rho = \frac{4}{3}\pi r^3 \delta \chi, \qquad (5)$$

where $\delta$ is the density of the matter of the particles.

The concentration of the particles and the volumetric density of the noctilucent clouds were calculated for different variations: for $r = 1.35 \cdot 10^{-5}$ and $1 \cdot 10^{-4}$ cm with $A^* = 1$ (i.e., it was assumed that the particles in the clouds were ice crystals); for $r = 1 \cdot 10^{-5}$ and $1 \cdot 10^{-4}$ cm with $A^* = 0.3$ (i.e., it was assumed that the particles were of meteoric origin). In this case, $\chi$ and $\rho$ were calculated for several diameters of the cloud layer (100,250,500,1000,2000, 2500 and 3000 m).

Calculations were made for the appearance of noctilucent clouds on July 15-16, 1959. Different concentrations of particles per unit volume were obtained for different details in the cloud field. However, we should assume that the concentration must be more or less identical throughout the entire cloud field, while the varying visible brightness of single details can be explained by the diameter of the cloud field in various directions along the line of sight. Therefore, it seemed of interest to determine the average concentration, and we attempted to do so. On the other hand, we had to know the vertical thickness (or the thickness along the line of sight) of the cloud layer for various details in the field before determining the average concentration. We did not know this value. Therefore, we found the average concentration in another way. In order to determine the probable average concentration, we calculated the average weight concentration for various thicknesses of the cloud layer. In this case, we used different weights for various details in the field with a definite thickness of the layer, depending on the intensity of the emission and the general structure of the field.

The weights used for various details in the field are shown in Table 3.

TABLE 3

| Detail of Cloud Field | Thickness of layer, m | | | |
|---|---|---|---|---|
| | 100–500 | 1000 | 2000 | 2500–3000 |
| Veil | 1 | 1/3 | 1/8 | 1/8 |
| Faint Crest | 2/3 | 1 | 1/4 | 1/4 |
| Bright Crest | 1/2 | 2/3 | 1 | 1/3 |
| Eddy Edge | 1/3 | 1/2 | 2/3 | 1/2 |
| Eddy | 1/4 | 1/4 | 1/2 | 2/3 |
| Eddy Center | 1/8 | 1/8 | 1/3 | 1 |

Naturally, these weights are rather arbitrary. However, considering /90
the fact that we were interested in any statistical average concentration in a first approximation, we permitted this inaccuracy.

The probable average weight concentrations obtained for various sections of the clouds are shown in Table 4.

TABLE 4

| Particle Characteristics | A* | Average Concentration $\overline{X}$, $cm^{-3}$ | Volumetric Density $\rho$ $g \cdot cm^{-3}$ |
|---|---|---|---|
| $r=1{,}35 \cdot 10^{-5}$ *см* | 1 | $3{,}3 \cdot 10^{-2}$ | $3{,}4 \cdot 10^{-16}$ |
| $r=1 \cdot 10^{-4}$ *см* | 1 | $6{,}1 \cdot 10^{-4}$ | $2{,}5 \cdot 10^{-15}$ |
| $r=1 \cdot 10^{-5}$ *см* | 0,3 | $1{,}8 \cdot 10^{-1}$ | $3{,}4 \cdot 10^{-15}$ |
| $r=1 \cdot 10^{-4}$ *см* | 0,3 | $1{,}8 \cdot 10^{-3}$ | $3{,}4 \cdot 10^{-14}$ |

We can assume that these average concentrations are rather approximate. Therefore, it would be very interesting to check these values by an indirect method.

We will introduce a new value, the so-called specific concentration of particles in noctilucent clouds $K'$. This value is determined by the following formula:

$$K' = \frac{n}{N}, \qquad (6)$$

where $n$ is the number of molecules in the atmosphere per unit volume; $N$ is the number of particles in noctilucent clouds of a certain size for the same volume.

We will also introduce a certain coefficient of proportionality $\alpha$, which will characterize the scattering capacity of the particles in the clouds relative to that of the molecules of the atmosphere;

$$K'' = \alpha \frac{n}{N}, \tag{7}$$

where $K''$ is a value which determines the quantity of light scattered by the particles in the noctilucent clouds relative to the light scattered by the molecules of the atmosphere.

In order to determine the nature of the light scattering in the zone of noctilucent clouds, we must determine the coefficient $\alpha$ in (7), which depends on the ratio $\alpha_\mu/\alpha_N$ (where $\alpha_N$ and $\alpha_\mu$ are the coefficients of the scattering of light by the cloud particles and by molecules in the atmosphere, respectively). However, it is insufficient to compare only total intensities in solving the problem of the nature of the light scattering in the atmosphere; we must also include the characteristic curves of the scattering, which can differ greatly for the scattering of light by particles and by molecules in the air. The particles (which have extended scattering curves) concentrate the scattered light in a narrow beam, while the molecules (which have Rayleigh curves) scatter light almost identically in all directions. Therefore, having compared the intensity of the light scattered by particles and molecules in the direction of the principal beam, we should examine only a small part of the scattered light flux in the case of molecular scatter, i.e., the part concentrated at that solid angle at which the light scattered by the particles is extended. In other words, if a particle scatters its principal flux at a solid angle $\gamma$, then we should consider the total light flux determined by the coefficient $\gamma/4\pi$ in a similar comparison with the light scattered by a molecule. /91

Returning to (7), we can now write the following:

$$\alpha = \frac{\alpha_M}{\alpha_N} \frac{\gamma}{4\pi} \tag{8}$$

and

$$K'' = \frac{\alpha_\mu}{\alpha_N} \frac{\gamma}{4\pi} \frac{n}{N}. \tag{9}$$

Let us determine $\alpha$. The scattering factor $\alpha_\mu$ calculated for one molecule of air with $\lambda$ = 5000Å gives $\alpha_\mu = 6.7 \cdot 10^{-27}$ cm$^2$ [4]. The scattering factor $\alpha_N$ for the particles can be calculated by the following expression:

$$\alpha_N = \pi r_N^2 k(\rho), \tag{10}$$

where $r_N$ is the radius of the particle and $\rho = 2\pi r_N/\lambda$; $k(\rho)$ is the scattering function tabulated in the work by Shifrin [5].

The value of the function $k(\rho)$ depends on the refractive index of the particle ($m$) in the following way:

| $m$ | $\lambda$, A | $r_N$, cm | $k(\rho)$ | $\alpha_N$, cm² |
|---|---|---|---|---|
| 1,33 | 5000 | $1,0\cdot10^{-5}$ | 0,19 | $6,28\cdot10^{-11}$ |
| 1,33 | 5000 | $1,0\cdot10^{-4}$ | 1,88 | $5,9\cdot10^{-8}$ |
| 1,33 | 5600 | $1,35\cdot10^{-5}$ | 0,32 | $1,0\cdot10^{-9}$ |
| 1,55 | 5000 | $1,0\cdot10^{-5}$ | 0,70 | $2,2\cdot10^{-10}$ |

Assuming that a particle scatters light at a solid angle $\gamma = (60-70°)^2$, we find that $\gamma/4\pi \approx 10^{-1}$.

In order to obtain the quantity of molecules which aid in producing the brightness of the twilight background for noctilucent clouds, i.e., the molecules of the atmosphere by which the solar light is scattered at a given zenith distance of the Sun, we calculated the following integral:

$$\int_{H_1}^{H_2} f(n)\,dn, \tag{11}$$

where $H_1$=70 km; $H_2$=700 km; $f(n)$ was taken according to the standard /92
atmosphere ARDC=1959 [6]. We obtained the value $n \approx 3.15\cdot10^{16}\,\mathrm{cm}^{-3}$.

In order to find the quantity of particles in noctilucent clouds, we will use (9), from which it follows that

$$N = \frac{1}{K''}\frac{\gamma\alpha_\mu}{4\pi\alpha_N} n, \tag{12}$$

where $K''$ can be replaced by the following expression:

$$K'' = \frac{b_{sk}}{b_0 - b_{sk}} \tag{13}$$

Here, $b_0$ and $b_{sk}$ have the same values as in (1). Formula (12) can now take the following form:

$$N = \frac{b_{sk}}{b_0 - b_{sk}}\frac{\gamma\alpha_\mu}{4\pi\alpha_N} n. \tag{14}$$

The quantity of particles $N$ per 1 cm³, i.e., the concentration $\chi$, was calculated for the noctilucent clouds on July 15-16, 1959 for the same details in the field as those whose brightnesses are shown in Table 2. The values of $\chi$ obtained are shown in Table 5.

As we can see from Table 5, the average concentrations obtained are rather close to the average weight concentrations obtained by the other method (see Table 4).

TABLE 5

| No. | Detail of Cloud Field | Concentration $\chi$ | | | |
|---|---|---|---|---|---|
| | | $m=1,33$ | | $m=1,55$ | |
| | | $r=1\cdot10^{-5}$ см | $r=1,35\cdot10^{-5}$* см | $r=1\cdot10^{-4}$ см | $r=1\cdot10^{-5}$ см |
| 1 | Veil ..... | $0,8\cdot10^{-1}$ | $0,5\cdot10^{-1}$ | $0,9\cdot10^{-4}$ | $0,3\cdot10^{-1}$ |
| 2 | Faint Crest . | $3,2\cdot10^{-1}$ | $2,0\cdot10^{-1}$ | $3,4\cdot10^{-4}$ | $0,9\cdot10^{-1}$ |
| 3 | Same....... | $5,1\cdot10^{-1}$ | $3,2\cdot10^{-1}$ | $5,4\cdot10^{-4}$ | $1,5\cdot10^{-1}$ |
| 4 | Bright Crest. | $3,3\cdot10^{-1}$ | $2,2\cdot10^{-1}$ | $3,6\cdot10^{-4}$ | $1,0\cdot10^{-1}$ |
| 5 | Eddy...... | $7,4\cdot10^{-1}$ | $4,6\cdot10^{-1}$ | $7,8\cdot10^{-4}$ | $2,5\cdot10^{-1}$ |
| 6 | Eddy Center · | $4,8\cdot10^{-1}$ | $3,0\cdot10^{-1}$ | $5,1\cdot10^{-4}$ | $1,4\cdot10^{-1}$ |
| 7 | Eddy Edge · · | $4,6\cdot10^{-1}$ | $2,9\cdot10^{-1}$ | $4,9\cdot10^{-4}$ | $1,3\cdot10^{-1}$ |
| 8 | Faint Crest · | $4,5\cdot10^{-1}$ | $2,8\cdot10^{-1}$ | $4,8\cdot10^{-4}$ | $1,3\cdot10^{-1}$ |
| 9 | Eddy...... | $3,6\cdot10^{-1}$ | $2,3\cdot10^{-1}$ | $3,9\cdot10^{-4}$ | $1,1\cdot10^{-1}$ |
| 10 | Eddy Center . | $4,2\cdot10^{-1}$ | $2,6\cdot10^{-1}$ | $4,4\cdot10^{-4}$ | $1,2\cdot10^{-1}$ |
| 11 | Same....... | $2,3\cdot10^{-1}$ | $1,4\cdot10^{-1}$ | $2,4\cdot10^{-4}$ | $0,7\cdot10^{-1}$ |
| | Average.... . | $4,0\cdot10^{-1}$ | $2,5\cdot10^{-1}$ | $4,2\cdot10^{-4}$ | $1,2\cdot10^{-1}$ |

Note: For $r=1.35.10^{-5}$cm, $\chi$ was calculated for $\lambda=5600$ Å; for the other values of $r$, it was calculated for $\lambda=5000$Å.

This circumstance allows us to consider that the average weight concentrations are more or less close to the real concentrations. /93

On the basis of these average weight concentrations, we calculated the effective thickness of the measured details in the cloud field for $r=1\cdot10^{-5}$cm according to (4). The results are shown in Table 6, where $\alpha'$ is the thickness of the layer along the line of sight, and $\alpha$ is the vertical thickness in relation to the Earth's surface.

According to Khvostikov's hypothesis, noctilucent clouds are formed as a result of condensation or sublimation of water vapor in the mesopause [7]. If we use the values for the concentration of particles we found in noctilucent clouds and the dimensions of the particles obtained from polarimetric observations [1,2], and if we also consider that the particles actually do consist of water, then the water content in noctilucent clouds is on the order of $10^{-9}$-$10^{-10}$g$\cdot$cm$^{-3}$, while the specific humidity corresponds to $g\approx10^{-6}$-$10^{-9}$.

TABLE 6

| No. | Detail of Cloud Field | Effective Thickness, m | | | |
|---|---|---|---|---|---|
| | | for $A^*=1$ | | for $A^*=0.3$ | |
| | | $\alpha'$ | $\alpha$ | $\alpha'$ | $\alpha$ |
| 1 | Veil . . . . . . . . | 580 | 130 | 650 | 180 |
| 2 | Faint Crest . . | 1 430 | 400 | 1 590 | 450 |
| 3 | Same . . . . . . . . | 1 010 | 340 | 1 120 | 370 |
| 4 | Bright Crest . . | 4 980 | 1520 | 5 540 | 1700 |
| 5 | Eddy . . . . . . . . | 5 300 | 1620 | 5 890 | 1800 |
| 6 | Eddy Center . . | 9 010 | 2190 | 10 060 | 2440 |
| 7 | Eddy Edge . . . . | 6 360 | 1620 | 7 080 | 1810 |
| 8 | Faint Crest . . | 1 270 | 340 | 1 420 | 420 |
| 9 | Eddy . . . . . . . . | 8 480 | 2020 | 9 430 | 2250 |
| 10 | Eddy Center . . | 14 840 | 3600 | 16 510 | 4000 |
| 11 | Same . . . . . . . . | 7 420 | 1920 | 8 270 | 2140 |

## 3. Determining the Characteristic Scattering Curves

Let us attempt to determine the characteristic scattering curves for the light of noctilucent clouds. We will assume that the average concentration of particles which form noctilucent clouds is everywhere identical in any structural shape of the field (in our case, in a band), and that the structural shape has the same effective thickness everywhere. Naturally, this assumption is rather risky, and can lead to a substantial deviation from the real values. Nevertheless, we did attempt to obtain some in- /94 formation concerning the nature of the scattering capacity of these particles despite this fact.

In order to do this, we used a photograph of noctilucent clouds obtained on July 30, 1959 at 23:49'45'' (apparent solar time) for the horizontal coordinates of the Sun $A = 177°32'$ and $z = 102°08'$. The exposure time was 30 sec, with a relative aperture of 1:22. A light filter (OS-11) was used. There were several bright bands on this photograph; they were almost parallel to the horizon throughout the entire cloud field.

We determined the brightness of 17 different points which had various angles of scatter but almost identical zenith distances for one such bright band. Therefore, we considered the extinction identical for all the points, and we made tests only for the photometric error in the field of the objective. The latter was determined under laboratory conditions with the aid of a photometric cube prepared specially for this purpose.

The measured brightnesses of the points in the band of noctilucent clouds are given in Table 7.

TABLE 7

| № | $\theta$ | $\frac{B}{B_0}$ | $\frac{B'}{B'_0}$ | № | $\theta$ | $\frac{B}{B_0}$ | $\frac{B'}{B'_0}$ |
|---|---|---|---|---|---|---|---|
| 1 | 20° | 0,84 | 1,04 | 10 | 30° | 0,77 | 0,78 |
| 2 | 22 | 0,98 | 1,12 | 11 | 32 | 1,00 | 1,00 |
| 3 | 23 | 0,79 | 0,89 | 12 | 34 | 1,00 | 1,01 |
| 4 | 24 | 0,73 | 0,79 | 13 | 35 | 0,66 | 0,67 |
| 5 | 25 | 0,84 | 0,89 | 14 | 37 | 0,68 | 0,70 |
| 6 | 26 | 0,98 | 1,03 | 15 | 38 | 0,71 | 0,75 |
| 7 | 27 | 0,89 | 0,92 | 16 | 39 | 0,56 | 0,60 |
| 8 | 28 | 0,72 | 0,74 | 17 | 41 | 0,52 | 0,59 |
| 9 | 29 | 0,78 | 0,79 | | | | |

Note: $\vartheta$ is the angle of scatter for the given point; $\frac{B}{B_0}$ is the brightness of the point in relative units, i.e., the ratio between the brightness of the given point ($B$) and that of the point at the center of the frame ($B_0$) (i.e., the 11th point) without corrections for the photometric error of the field; $\frac{B'}{B_0'}$ is the same error, but without the field error.

On the basis of the data obtained, we constructed the scattering curve in the form of a vector diagram (Fig. 2).

The scale of the curves varies. Curve IV (broken line) was plotted as an estimate of the average values for the 17 points.

The first three curves were taken according to Shifrin [5]. /95
They are the characteristic curves of weakly-refracting particles such as those forming noctilucent clouds (in all probability).

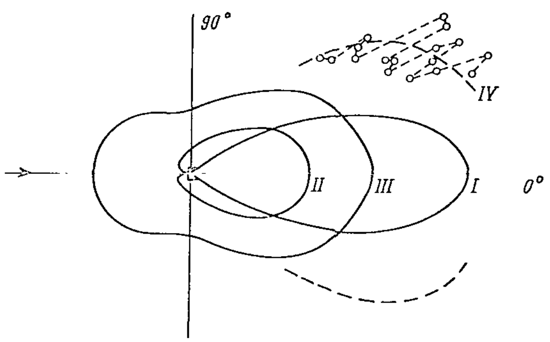


Fig. 2. Characteristic Curves of Weakly Refracting Particles (I-III), and the Characteristic Curve of Particles in Noctilucent Clouds, Obtained from Observations (IV). (I) Curve for Particles with $m\frac{2\pi r}{\lambda} = 4$; (II) for Particles with $m\frac{2\pi r}{\lambda} = 1.6$; (III) for Particles with $m\frac{2\pi r}{\lambda} = 0.8$.

As we can see from Figure 2, the variation of our points is rather great. This can be explained by our assumption that the concentration of particles is identical throughout the entire band. Therefore, Curve IV (which is the characteristic curve of particles in noctilucent clouds) is a rough approximation of the real one. We can also see that there is a certain resemblance between Curves II and IV. This means that the same order of magnitude for the dimensions of the particles in noctilucent clouds was obtained from the polarimetric studies observing the same phenomenon and for Curve IV.

## 4. Determining the Brightness Function and the Transmission Coefficient of Noctilucent Clouds

As we can see from the results obtained, the apparent brightness of noctilucent clouds varies within a rather broad range (in our cases, from $28 \cdot 10^{-6}$ to $2.4 \cdot 10^{-11}$, in solar brightness units) in relation to the intensity of the cloud field for the phenomenon and the angle of scatter for the point whose brightness is determined. In all probability, this variation in the brightness was caused primarily by the concentration of particles, which can vary /96 for different occurrences (naturally, within certain limits). We can also assume that the effective thickness of the cloud layer is not constant for different occurrences. However, a change of the latter to a degree that would give values on the order of 5-6 for the variation in the brightness of the details in the cloud field is not very likely. Moreover, we can hardly consider the variation in the dimensions of the particles for different occurrences as the principal cause of such a broad interval for the change in the brightness. The results of polarimetric observations [2] also contradict such an assumption.

If we assume that the particles in noctilucent clouds are formed by sublimation of water vapor, then the dimensions of the particles will not be constant (obviously) and will depend on the duration of the conditions suitable for sublimation and the quantity of water vapor in the zone where the noctilucent clouds are formed.

Using Hesstvedt's formula [8], we can calculate the rate of sublimation and the time when the particles are being formed:

$$\frac{dr}{dt} = \frac{\alpha e}{\rho_i} \sqrt{\frac{M}{2\pi RT}} \left[ 1 - \frac{e_i(r)}{e} \right], \qquad (15)$$

where $r$ is the radius of a particle; $t$ is the time; $M$ is the molecular weight of ice; $\rho_i$ is the density of the ice; $R$ is the universal gas constant; $T$ is the temperature; $e$ is the pressure of the ambient water vapor; $e_i(r)$ is the equilibrium vapor pressure at the surface of the particle; $\rho$ is the coefficient of sublimation.

The unknown values on the right-hand side of the equation ($\alpha, \rho_i$, $T$ and the numerical value of $[1-\frac{ei(r)}{e}]$ can be shown with an accuracy sufficient for determining the correct order of magnitude for $dr/dt$ (at least). Using the data of various researchers, and extrapolating the results of measurements for the humidity at heights of 28-82 km, it was found that $dr/dt = 10^{-7}$ cm/min [8]. This means that about thirty minutes is necessary for the process of formation of the particles in noctilucent clouds with the dimensions we obtained from polarimetric studies ($1.35 \cdot 10^{-5}$ cm). According to our observations and the data in the literature, the continuous increase in the emission intensity of noctilucent clouds, and thus the continuous increase of particles, occurs during the same time interval; the former sometimes occurs more slowly than the latter.

According to the shape of the characteristic curve we obtained (which, naturally, is only a first approximation of the real one) and the theoretical characteristic curves for weakly-refracting particles with $2\pi r/\lambda = 0.8-2.5$ (which, according to polarimetric observations, also form noctilucent clouds), the brightness of a detail in the cloud field can change, depending on the angle of scatter (with 0<< <<90°) within the range of orders of magnitude /97
from 0.3 to 2.0. It follows from this that the various angles of scatter can also be the cause of this wide brightness range for the field of noctilucent clouds.

The brightness of noctilucent clouds ultimately depends on all the factors mentioned. The latter factors (except the angle of scatter), i.e., the concentration and dimensions of the particles and the effective thickness of the cloud layer, depends on the physical conditions for the sublimation in the zone where noctilucent clouds are formed. These conditions are the corresponding temperature and pressure and a sufficient quantity of water vapor and sublimation nuclei.

Considering what we have said, the brightness of the cloud field can be expressed as a function of these parameters, i.e.:

$$B_0 = F(T, p, a, n, \Delta t, 0), \qquad (16)$$

where $T$ is the temperature; $p$ is the pressure, $a$ is the water-vapor content in the atmosphere (the ratio between the concentration of $H_2O$ molecules and the total concentration of all the molecules); $n$ is the number of sublimation nuclei (dust particles, micrometeors); $\Delta t$ is the time from the beginning of sublimation to the moment of the observation;  is the angle of scatter for the given point.

The relationship between the radius of an ice crystal $r$ and the time of its growth can be expressed by the following formula [9]:

$$r = \left(2D\frac{\rho_a}{\rho_i}\Delta qt\right)^{1/2}, \tag{17}$$

where $D$ is the coefficient of diffusion; $\rho_a$ and $\rho_i$ are the densities of the atmosphere and the ice, respectively; $\Delta q$ is the supersaturation, i.e., the difference between the specific atmospheric humidity and the saturated humidity for a given temperature; $t$ is the time for the growth of the crystal.

Expressing $D$ in terms of the pressure $p$ and the temperature $T$, we can write the following:

$$D = D_0\frac{p_0}{p}\left(\frac{T}{T_0}\right)^{1,81}, \tag{18}$$

where the subscript "0" signifies the standard conditions.

Equation (17) can now be written thus:

$$r = \left[2D_0\frac{p_0}{p}\left(\frac{T}{T_0}\right)^{1,81}\frac{\rho_a}{\rho_i}\Delta qt\right]^{1/2} \tag{19}$$

Expressing the value $r$ in (4) in terms of (19), and deriving $A_B$ from (4) (which is essentially the same as $B_0$), we can obtain the following:

$$B_0 = \chi\pi\left[2D_0\frac{p_0}{p}\left(\frac{T}{T_0}\right)^{1,81}\frac{\rho_a}{\rho_i}\Delta qt\right]^{1/2} d\sec\left[\arcsin\left(\frac{R}{R+H}\right)\right]f(\theta), \tag{20}$$

where the symbols are the same as in (4); $A^*$ in (4) was considered equal to one. /98

The formula obtained links the principal parameters presented in (16). We could not include the function $f(\theta)$ in (20) more clearly, since there is no precise characteristic for the light scattering by particles in noctilucent clouds.

From the point of view of astrophysical observations, the extinction of light in passing through the layer of noctilucent clouds is of particular significance. Let us attempt to determine it on the basis of our observations.

The optical thickness of the layer $\tau$ in the case of ice crystals in the air can be expressed by the following formula [9]:

$$\tau = \frac{\overline{m}}{\rho_i \overline{r}}, \tag{21}$$

where $\overline{m}$ is the average mass of the ice crystals in the air in the vertical column of a single section; $\rho_i$ is the density of the ice; $r$ is the average size of the crystals.

On the other hand, $\tau$ can be expressed in the following way:

$$\tau = \int_0^x \alpha(x)\,dx, \tag{22}$$

where $\alpha$ is the coefficient of extinction; $\chi$ is the total thickness of the layer.

Considering the medium of the noctilucent clouds to be optically homogeneous and the value of the coefficient of extinction $\alpha$ identical at all of its points, we have the following:

$$\tau = \alpha x, \tag{23}$$

The exponential law of extinction can now be written thus:

$$T = e^{-\alpha x}, \tag{24}$$

where $T$ is the transmission coefficient.

Considering that the value of $\alpha x$ in (24) was not clear in (21), we can write the following:

$$T = e^{-m/\rho_i \overline{r}} \tag{25}$$

or

$$T = 10^{-\frac{m}{\rho_i \overline{r}} \log e} \tag{26}$$

Considering the average dimensions of the particles in noctilucent clouds equal to $r \approx 1.35 \cdot 10^{-5}$ cm, the average volumetric density of the particles equal to $\approx 3.4 \cdot 10^{-16}$ $g \cdot cm^{-3}$ (see Table 3), and the average diameter of the clouds $d \approx 10^{-5}$ cm (see Table 6), we can find from (26) that $T \approx 0.99 \approx 1$.

As we can see, the transmission coefficient of noctilucent clouds is close to one. This means that the screening of the light flux penetrating the cloud layers is very weak. /99

The data in the literature and our own experiments show that there is no significant screening of celestial bodies located beyond a field of noctilucent clouds.

## 5. Conclusion

The results of photometric observations show that the absolute brightness of noctilucent clouds can vary within a rather broad range. The principal reason for this, in all probability, is the variation in the concentration of particles, both for different occurrences and in the course of the same occurrence. Thus, we are concerned with those particles in noctilucent clouds whose formation or accumulation depends on some specific conditions. The hypothesis that noctilucent clouds consist only of small particles of cosmic dust can hardly explain the rather rapid change in the quantity of particles in the zone of noctilucent clouds which follows from visual observations as well as from photometric data on the variation in the brightness of single details and of the cloud as a whole. Therefore, it is more natural to assume that these particles are formed at the site, to a certain degree, and that their quantity and rate of formation depend on the physical conditions and the quantity of initial materials (for example, water vapor) for which the rather rapid change is more natural.

We will now discuss these problems briefly.

It is well known that there are two principal hypotheses concerning the origin of noctilucent clouds. According to one of them, the so-called condensation hypothesis, noctilucent clouds consist of ice crystals, i.e., they are the product of sublimation. According to the other, the so-called meteoric-dust hypothesis, noctilucent clouds consist of small dust particles which are primarily of cosmic origin. There is also another, so-called compromise, variation, according to which the dust particles are considered to be sublimation nuclei and to act as accelerators of the formation of ice crystals.

Both the first and the second hypotheses involve a number of problems which have not been solved, and the mechanism for the origin of noctilucent clouds has still not been established conclusively. Therefore, it would be very desirable to obtain new data and ideas concerning the processes occurring in the upper layers of the atmosphere, which could be used in solving the problem of the origin of noctilucent clouds. Moreover, each new fact concerning the nature and behavior of noctilucent clouds aids in a more complete solution to this problem. In our opinion, one such /100
rather important fact is the quantitative change in the concentration during a given appearance of noctilucent clouds.

The most disputed questions concerning the condensation hypothesis are the following:

(1) Is the temperature in the mesopause, in the zone where noctilucent clouds are formed, low enough for the water vapor to become saturated relative to the ice, and is precipitation of water vapor possible?

(2) Is there a sufficient quantity of water vapor in the zone where these clouds are formed?

I.A. Khvostikov [10] answered the first question. Using factual data concerning the temperature regime of the upper layers of the atmosphere, he showed that the temperature in the mesopause decreases from winter to summer at a latitude of about 60°N, and that during the summer the temperature there (even the average temperature) is close to those "rather low" values which are necessary for the formation of noctilucent clouds. This fact also explains why noctilucent clouds appear only during the summer and in a narrow latitudinal band.

There are various opinions concerning the second question, or how the water vapor appears in the mesopause. Some authors maintain that the water vapor is transported there from the troposphere by ascending air currents (N.I. Grishin [11]); others are of the opinion that it is formed at that site in the upper layers of the atmosphere (I.A. Khvostikov [7], C. de Turville [12], D.J. Schove [13], R. Frith [14]), or is transported there from outer space by meteors, and that the water is liberated as a result of the disintegration of the meteors at 80-90 km (S.P. Dobrovol'skiy [15]). In our opinion, the second version deserves the most attention.

As long as ten years ago, I.A. Khvostikov proposed the idea that $H_2O$ molecules are formed of protons (brought into the atmosphere by corpuscular streams of solar origin) and atmospheric oxygen. This problem was studied in more detail by C. de Turville. According to his data, the constant proton flux trapped by the geomagnetic field up to a distance of about 12 Earth radii leads to an increase in the mass of hydrogen in the atmosphere to such a degree that the value of the trapped solar hydrogen is comparable to the quantity of hydrogen in the waters of the Earth's oceans ($1.24 \cdot 10^{24}$g) (if it is assumed that the accretion has occurred at the same rate throughout the entire time that the Earth has existed, i.e., $3.3 \cdot 10^9$ years). Therefore, C. de Turville suggested that there is a continuous process of water formation at a rate of 1.5 tons/day in the upper atmosphere of the Earth; this is subsequently differentiated below these levels.

Having studied the problems of the distribution of water vapor by altitude and geographic latitude by analyzing actually observed data, D.J. Schove drew the following conclusions:

(1) The highest concentration of water vapor in the lower stratosphere occurs around the middle of the summer, when the quantity of water vapor at an altitude of 100 mb (16 km) reaches 200-300 mg/kg; /101

(2) There is a systematic annual cycle of concentrations of water vapor, with a maximum concentration during the summer and a minimum during the winter. This involves latitudes north of 45°N;

(3) The amplitude of the annual variation is highest around the middle of the winter, and it decreases with a decrease in latitude;

(4) The quantity of the concentrations increases in high latitudes with an increase of the altitude.

Finally, he maintained that the Earth's surface is hardly the only source of the water vapor found in higher layers of the atmosphere.

R. Frith suggested that the water vapor formed in the mesopause is transported into the stratosphere turbulent mixing. G. Warnecke [16] assumed that the principal cause of the circulation between the lower mesosphere and the upper stratosphere was a long-lasting circumpolar anticyclone during the summer.

Since the relatively greatest quantity of vapor is found during the summer (solar time) at a northern latitude of about 60°, the idea that noctilucent clouds are formed from the water formed at the site in the mesosphere as a result of some process (for example, the photochemical process $OH + H \rightleftarrows H_2O$) is very convincing. It is well known that the bands found in the spectrum of the night sky indicate the presence of OH at an altitude of about 70-80 km. This idea should be studied in greater detail.

I would like to mention one more interesting observed fact: noctilucent clouds appear in some kind of series, i.e., it often happens that they appear two, three, or even more nights in sequence. This fact has not been interpreted conclusively.

Finally, I should mention that the problems related to the mechanism for the origin of noctilucent clouds show that new observational data will have to be accumulated and studied in great detail in the future.

In conclusion, I would like to say that noctilucent clouds, which are a phenomenon in the upper layers of the atmosphere, are an excellent agent by which the processes occurring in these layers of our planet, as well as other planets, can be examined.

## REFERENCES


1. Villmann, C.I.: Trudy soveshchaniya po serebristym oblakam (Works of a Conference on Noctilucent Clouds), Vol. III. Tallin, 1962, pp. 38-58. /102
2. Villmann, C.I.: Nekotoryye rezul'taty izucheniya prirody serebristykh oblakov (Some Results of a Study of the Nature of Noctilucent Clouds). Author's Abstract, 1963.
3. Villmann, C.I.: Trudy VI Soveshchaniya po serebristym oblakam (Works of the Sixth Conference on Noctilucent Clouds). Tartu, 1961, pp. 25-34.
4. Kondrat'yev, K.Ya.: Luchistaya energiya Solntsa (The Radiant Energy of the Sun). "Gidrometeoizdat", 1962.
5. Shifrin, K.S.: Rasseyaniye sveta v mutnoy srede (Light Diffusion in a Cloudy Medium). Moscow, 1951.
6. Kondrat'yev, K.Ya.: Meteorologicheskiye issledovaniya s pomoshch'yu raket i sputnikov (Meteorological Studies with the Aid of Rockets and Satellites). "Gidrometeoizdat", 1962.
7. Khvostikov, I.A.: Serebristyye oblaka i stroyeniye stratosfery (Noctilucent Clouds and the Structure of the Stratosphere), in: Sbornik Pamyati S.I. Vavilova (Collection Dedicated to S.I. Vavilov). Izdat. Akad. Nauk S.S.S.R., 1952, pp. 349-362.
8. Hesstvedt, E.: J. Geophys. Res., Vol. 66, No. 6, pp. 1985-1987, 1961.
9. Lebedinskiy, A.I. and G.I. Salova: Astron. Zhur., Vol. 39, No. 3, pp. 494-505, 1962.
10. Khvostikov, I.A.: Trudy Soveshchaniya po serebristym oblakam (Works of a Conference on Noctilucent Clouds), Vol. III. Tallin, 1962, pp. 7-13.
11. Grishin, N.I.: Trudy VI Soveshchaniya po serebristym oblakam (Works of the Sixth Conference on Noctilucent Clouds). Riga, 1961, pp. 107-140.
12. de Turville, S.M.: Terrestrial Accretion from the Solar Wind. Nature, Vol. 190, No. 4771, p. 156, 1961.
13. Schove, D.J.: A Secondary Source of Water Vapor in the Upper Atmosphere. Nature, Vol. 197, No. 4872, pp. 1099-1101, 1963.
14. Frith, R.: Nature, Vol. 191, p. 1182, 1961.
15. Dobrovol'skiy, S.N.: O prirode serebristykh oblakov (The Nature of Noctilucent Clouds), in: Tsirkulyar VAGO (Circular of the All-Union Astronomical and Geodetic Society), No. 5, pp. 31-34, 1962.
16. Warnecke, G.: Berliner Wetterkarte (Berlin Weather Map). Berlin, 1961.

# OBSERVATIONS OF NOCTILUCENT CLOUDS AT SMOLENSK IN 1959-1961

B.S. Mamontov

*ABSTRACT: This article gives a description of the observations of noctilucent clouds at Smolensk in 1959-1961. No relationship was found between the appearances of noctilucent clouds and the meteorological phenomena. It was concluded that observations should begin in April and end in September, since advantageous conditions for the appearance of noctilucent clouds occur during these times.*

The Smolensk division of the All-Union Astronomical and /102
Geodetic Society began regular observations of noctilucent clouds in 1959. The observations were conducted according to the instructions for observations of noctilucent clouds in the following program:

(1) Recording the appearances of noctilucent clouds,

(2) Determining the seasonal and time for appearances of noctilucent clouds,

(3) Obtaining photographs,

(4) Theodolite observations.

The FED-2 cameras, with objectives "Industar-50" (1:3.5) and "Industar 26-M" (1:2.8), and a TT-50 theodolite were used for the observations.

The observations began on June 28, 1959, when the first appear- /103
ance of noctilucent clouds was recorded from 2215 to 2310 in the form of diffuse bands of the Types I and II-a, with a brightness 2 (in the five-number scale). Three of the eight appearances of noctilucent clouds in July, 1959 were of maximum brightness (5).

The noctilucent clouds with a brightness of 5 were observed on July 7; they began to appear at 0100. Almost all the morphological forms were present: I, II-a, III-b, IV-a, IV-b. The noctilucent clouds developed very rapidly, reorganizing from one shape to others. At 0345, the noctilucent clouds ceased to be visible against the background of the sky, which was growing light.

On the night of July 10-11, the noctilucent clouds observed from 2245 to 0235 had a brightness of 5. The clouds noted at the northeast had a brightness of 2, and were of Type II-b. This group lasted until 2330. At 2345, a veil appeared in the northeast; the veil developed rapidly together with the first group. Both sections of noctilucent clouds shifted along the horizon from the northeastern part of the sky toward the northwest (from right to left). The left-hand group of noctilucent clouds, having gone beyond the limits of the twilight segment, disappeared at 0045, while the right-hand group of clouds had reached maximum brightness by that time, shifted toward the northwestern part of the twilight segment, and became the principal group of noctilucent clouds. By 0235, they ceased to be visible against the background of the sky. Morphological types I, II-a, II-b, and III-b were present.

At 2350, two segments of a veil with a brightness of 1 were formed at the northeastern part of the band which had disappeared; by 2355, they had grown into a general bank from Cassiopeia to the Northern Cross, and by 0003, the entire bank had shifter by 10° from Cassiopeia to Altair. By 0006, the veil had become insignificant against the background of the Milky Way. Twenty-six negatives of noctilucent clouds were obtained that night on an isopanchromatic film of 250 units (All-Union State Standard) (Fig. 1).

Bright clouds (brightness 5) were also observed on the night of July 13-14, 1959. They lasted from 2250 to 0300. Morphological types I, II-a, II-b, III-a, III-b, III-c, and IV-a were present. Before midnight, the noctilucent clouds moved from the right to the left; after midnight, they began to move from the left to the right. Thirty-one negatives were obtained on an isopanchromatic film of 250 units (All-Union State Standard) (Fig. 2).

Six negatives of noctilucent clouds were obtained for the night of July 14-15. No noctilucent clouds were recorded in August, 1959. The results of the observations in 1959 are shown in Table 1.

In 1960, the observations of noctilucent clouds were begun in May, but the first appearance of noctilucent clouds were recorded on June 30. The clouds had a brightness of 2, and were found in the form of parallel III-b bands; they lasted from 0010 to 0040.

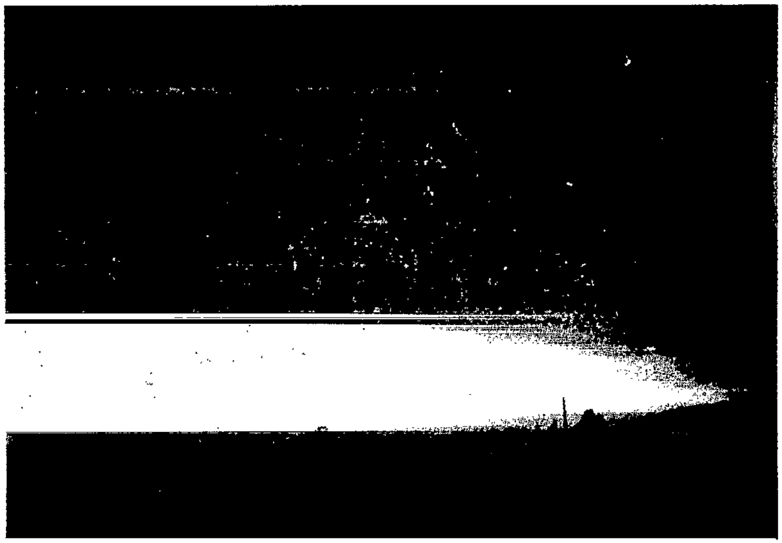

Fig. 1. Noctilucent Clouds at Smolensk on June 10-11, 1959, at 0029. Exposure Time, 45 sec. FED-2. "Industar-50", 1:3.5. $A$ = 140-180°. Photo by the Author.

TABLE 1. OBSERVATIONS OF 1959

| Date | Time of IIIrd Zone Begin | | End | | Maximum Brightness Scale | Structure |
|---|---|---|---|---|---|---|
| 28–29 Jun | 22 hr | 15 min | 23 hr | 10 min | 2 | I, II—*a* |
| 2–3 Jul | 23 | 50 | 00 | 50 | 2 | I, II—*a*, IV-b, |
| 5–6 | 23 | 20 | 23 | 45 | 2 | |
| 6–7 | 1 | 00 | 3 | 45 | 5 | I, II—b, III—b, IV—*a* IV—b |
| 10–11 | 23 | 50 | 2 | 35 | 5 | I, II—*a*, II—b, III—b |
| 11–12 | 23 | 45 | 0 | 20 | 1 | |
| 13–14 | 22 | 50 | 3 | 00 | 5 | I, II—*a*, II—b III—*a*, III—b, III—c IV—*a* |
| 20–21 | 22 | 20 | 0 | 30 | 2 | I, II—*a* |
| 14–15 | 22 | 15 | 3 | 00 | 3 | II—*a*, III—b |

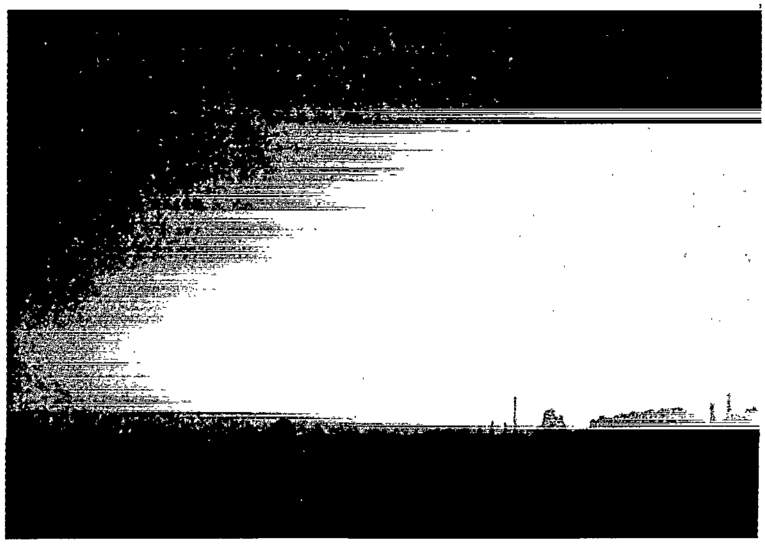

Fig. 2. Noctilucent Clouds at Smolensk on July 13-14, 1959. Time, 0000; Exposure, 15 sec; FED-2; "Industar-50", 1:3.5; $A$ = 140-180°. Photo by the Author.

There were few advantageous nights for observations in July and August, because of the cloudy and inclement weather. The weather was clear in September, and 3(!) appearances of noctilucent clouds were recorded from September 13 to 30 (on the nights of September 17-18, 18-19, and 19-20). On the night of September 18-19, the photographs of noctilucent clouds were made on "Isopan F" film (90 units, All-Union State Standard); 28 negatives were obtained, but we could distinguish only 10 noctilucent clouds.

All the noctilucent clouds observed in September, 1960 were no brighter than 3. They were of morphological types I, II-a, and III-a. The air temperature at the Earth's surface dropped to -3°C on the nights the clouds appeared. The air pressure was on the order of 750 mm Hg for the observation site on the night the noctilucent clouds appeared.

All the data concerning the noctilucent clouds observed in 1960 are shown in Table 2.

The first appearance of noctilucent clouds in 1961 was recorded on April 23, from 0340 to 0505; the clouds were of types I,II-a and IV-c, were found in the northern and northeastern parts of the sky, and had a maximum brightness of 3. /106

TABLE 2. OBSERVATIONS OF 1960

| Date | Time of IIIrd Zone Begin | | Time of IIIrd Zone End | | Maximum Brightness Scale | Structure |
|---|---|---|---|---|---|---|
| 29–30 Jun | 0 hr | 10 min | 0 hr | 40 min | 2 | III–b |
| 17 Sep | 20 | 20 | 20 | 32 | 3 | 4 blurred II-a bands |
| 18–19 | 20 | 00 | 6 | 20 | 3 | I, II–*a* |
| 19 | 20 | 00 | 20 | 35 | 1 | I, II–*a* |

Fig. 3. Noctilucent Clouds at Smolensk on July 20-21, 1961. Time, 0100; Exposure, 30 sec; FED-2; "Industar-50", 1:2.8; *A* = 155-210°; Photo by the Author.

In its external appearance, the principal section of the noctilucent clouds at the north resembled a ragged piece of fabric. Its edges were brighter than the principal field, and they diverged from the center of the field. By 0430, the clouds had become faint, /107 and they reached the zenith and were even found beyond the zenith, toward the south. At 0505, the sky became light, and the observations were stopped. The weather was cold and slightly windy, there was frost on the ground, and the night was extremely clear; there were only the usual clouds somewhere on the horizon.

One appearance of noctilucent clouds was recorded in May, on the night of May 9-10, from 2205 to 0110. The brightness of these clouds reached 3, and morphological types I and II-a were found.

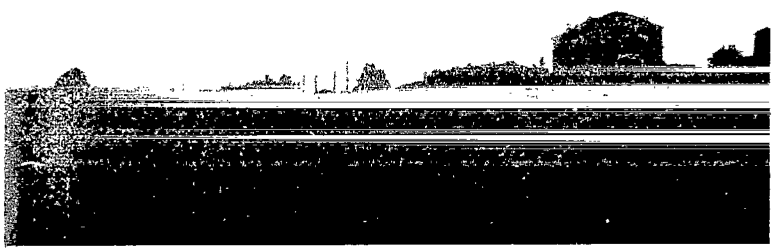

Fig. 4. Noctilucent Clouds at Smolensk on June 20-21, 1961. Time, 0141; Exposure, 30 sec; FED-2; "Industar-26-M", 1.2.8; $A$ = 155-210°. Photo by the Author.

Seven appearances of noctilucent clouds were recorded in June. The brightest clouds were observed on the night of June 20-21, from 2310 to 0300; their brightness was 5. The following morphological types were present: I, II-a, II-b, III-b, III-a, III-c, and IV-a. The night was cold. Forty-five frames were taken: 10 on an isopan film of 250 units (All-Union State Standard), and 35 on an isopan of 180 units (Figures 3 and 4).

Negatives of noctilucent clouds were also obtained on the nights of June 4, 5-6, 6, 8, 14-15, and 16-17. On the night of June 5-6, we obtained a series of negatives of a "beam" in the southern part of the sky; it appeared together with noctilucent clouds, and also when there were no noctilucent clouds, but always in clear weather. The city and valley of the Dniepr River were illuminated on the southern side. The "beam" was also observed over this site. /108

TABLE 3. OBSERVATIONS OF 1961

| Date | Time of IIIrd Zone | | Maximum Brightness Scale | Structure | Comment |
|---|---|---|---|---|---|
| | Begin | End | | | |
| 23 Apr | 3 hr 40 min | 5 hr 00 min | 3 | I, II-a, IVc | Frost on Ground |
| 9—10 May | 22 05 | 1 10 | 3 | I, II-a | Light Wind "Beam" at South |
| 4 Jun | 0 15 | 0 55 | 1 | II-a | Bands of Veil Among |
| 5—6 | 23 30 | 2 45 | 2 | I, II-a | Noctilucent Clouds |
| 6 | 22 00 | 24 00 | 3 | I, II-a, II-b, IV-b | Noctilucent Clouds Visible Among Traces |
| 8 | 1 00 | 4 00 | 3 | I, II-a | from Aircraft |
| 14—15 | 23 30 | 1 30 | 2 | I, II-a | Normal White Clouds at Zenith |
| 16—17 | 23 15 | 2 30 | 3 | I, II-a, II-b | Cold Night |
| 20—21 | 23 10 | 3 00 | 5 | I, II-a, II-b, III-a, III-b, III-c, IV-a | Same |
| 9 Jun | 0 00 | 2 15 | 2 | II-a, II-b | |
| 12—13 | 23 00 | 0 05 | 3 | I, II-a, II-b | Haze on Horizon |

Two appearances of noctilucent clouds were recorded in July: July 9 and 12-13. The brightness of these clouds were 3.

In August, the observer G.T. Vol'vachev recorded two appearances of noctilucent clouds with brightnesses up to 2 and Types I and II-a.

All the data on the observations of noctilucent clouds in 1961, except the observations of G.T. Vol'vachev, are shown in Table 3.

A great deal of data was accumulated during the three-year period of noctilucent cloud observations from 1959-1961. Some of these data are given in Table 4 and Figures 5-7.

All the data on the observations of noctilucent clouds at Smolensk in 1959-1961 (logs, films, photographic charts, descriptions of the noctilucent clouds) were given to the Special Committee of the All-Union Astronomical and Geodetic Society.

In concluding the results, we can mention the following:

(1) The maximum occurrences of noctilucent clouds over Smolensk are seen in the interval between the first half of June and the first half of July.

(2) During different years, the maximum occurrences of noctilucent clouds are seen, not only at different days of the month, but also in different months.

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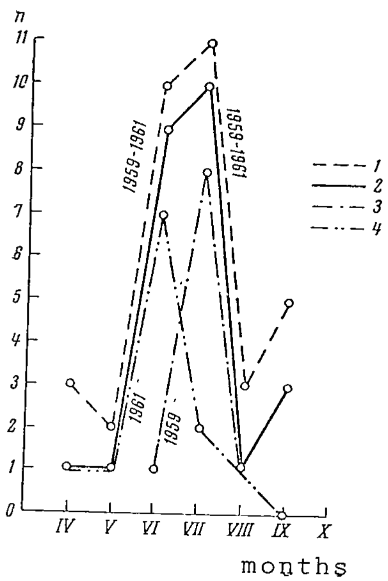


Fig. 5. Distribution of the Number of Appearances of Noctilucent Clouds ($n$) at Smolensk by Months, for 1959-1951. (1) All Cases of Appearances (Including Doubtful Ones); (2) All Reliable Cases of Appearances; (3) Appearances during 1959; (4) Appearances during 1961.

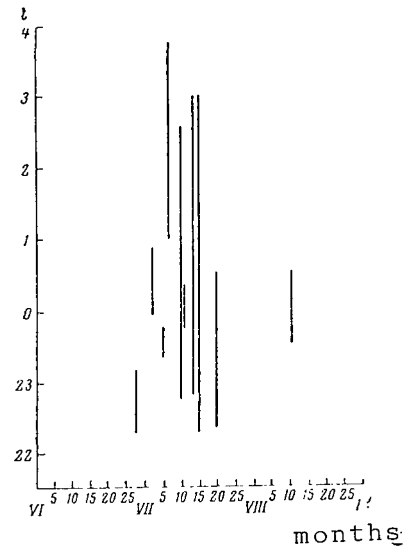


Fig. 6. Relationship between the Duration of the Noctilucent Clouds and the Date of Their Appearances in 1959, at Smolensk.

Moscow Time.

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TABLE 4. DATA CONCERNING THE OBSERVATIONS OF NOCTILUCENT CLOUDS AT SMOLENSK FOR 1959-1961

| Month | 1959 | | 1960 | | 1961 | | 1959-1961 | |
|---|---|---|---|---|---|---|---|---|
| | No. of Appearances Noctilucent Clouds | | | | | | Total No. of Appearances | |
| | Rel | all cases | Rel | all cases | Rel | all cases | Rel | all cases |
| April | - | - | - | 1 | 1 | 2 | 1 | 3 |
| May | - | - | 0 | 0 | 1 | 2 | 1 | 2 |
| June | 1 | 1 | 1 | 1 | 7 | 8 | 9 | 10 |
| July | 8 | 8 | - | - | 2 | 3 | 10 | 11 |
| August | 0 | 1 | - | - | 1 | 2 | 1 | 3 |
| September | - | - | 3 | 5 | 0 | 0 | 3 | 5 |
| For Entire Year | 9 | 10 | 4 | 7 | 12 | 17 | 25 | 34 |

Note: The dashes indicate that there were no observations during the month in question.

The following data give an example of this: in 1959, the maximum occurrences of noctilucent clouds were seen during the first /110

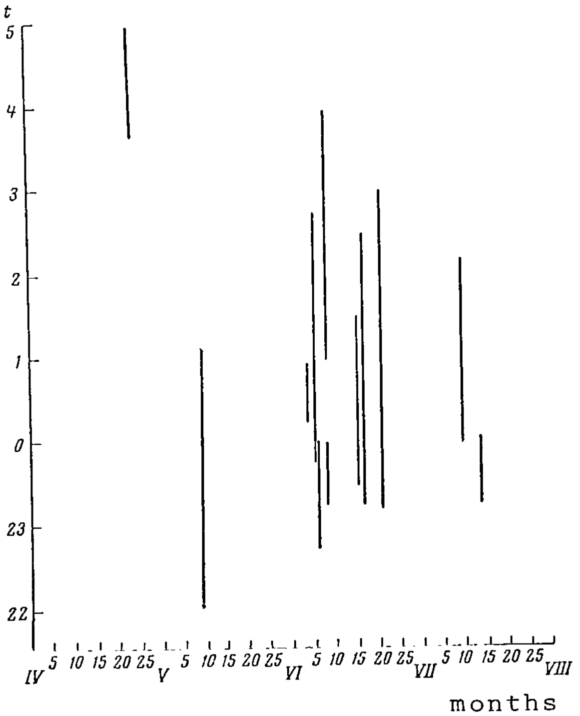


Fig. 7. Relationship between the Duration of the Noctilucent Clouds and the Date of Their Appearances in 1959, at Smolensk.

Moscow Time.

half of July; in 1961, they were seen during the first half of June (see Figures 5-7).

(3) It is correct to assume that the most intensive appearances of noctilucent clouds can be observed after the temperature has ceased to increase. During such nights, the twilight segment should be observed most carefully, since bright noctilucent clouds with a complex structure are often noted after nights when there are no noctilucent clouds.

(4) It was noted that on the nights following the appearance of bright noctilucent clouds, other noctilucent clouds appear whose intensity decreases from night to night. We can also have the opposite picture: bright clouds precede faint noctilucent clouds by one or two weeks. The subsequent noctilucent clouds are usually /111
of Types I and II-a, and are very stable in time. This leads us to think that noctilucent clouds can exist a rather long time, on the order of several days.

(5) There was no relationship observed between the appearances of noctilucent clouds and meteorological phenomena. However, we should note that the noctilucent clouds observed in September, 1960 were accompanied by increased atmospheric pressure, on the order of 760 mm Hg (750 is normal for Smolensk).

(6) Observations of noctilucent clouds should begin in April and end in September, since there are some advantageous conditions (which we still have not defined) for noctilucent clouds both in April and in September. Maximum attention should be given to the observations in June and July.

# OBSERVATIONS OF NOCTILUCENT CLOUDS AT RYAZAN IN 1961

Ye.Ye. Artemkin and V.I. Kuryshev

*ABSTRACT: The authors of this article discuss the three cases when noctilucent clouds were observed over Ryazan in 1961.*

In 1961, three cases of appearances of noctilucent clouds were recorded at Ryazan: on June 20, July 3, and July 28. /111

The observations were conducted at the observation area of the Ryazan Optical Station by Ye.Ye. Artemkin, V.I. Kuryshev, Ye.B. Gusev, T.A. Savost'yanova, and others. The instruments were commander's zenith telescopes.

The noctilucent clouds of June 20 were observed from 2030 to 2315 Universal Time. The general brightness of the clouds did not exceed brightness 1 (in the five-number brightness scale), although single formations were brighter (up to 2). The structure of the clouds was not clear; a veil predominated, and there were single bands and waves. The clouds changed structure rapidly: at 2200, the clouds had the characteristic structure of crests, and sharp bands in the form of streams could be distinguished. The sky was clear (cloudless), and there was no moon. It was very cold on the evening of this night. The results of the observations are shown in Table 1.

The clouds of July 3 were observed from 2020 to 2306. The noctilucent clouds were observed in the form of bands, waves, and streams. The veil was not very clear, but the bands, eddies, and crests were sharply distinguished. The clouds changed their structure rapidly, and the clearly outlined structures eventually became blurred formations and veils. The brightness of the clouds did not exceed 1-1.5, and the atmospheric temperature was no greater than +14°C. Single bands of noctilucent clouds disappeared, "melting" before our eyes, at 2306. /112

The results of the observations are given in Table 2.

TABLE 1.

| Universal Time | Brightness (5-scale unit) | Azimuths and Heights of Characteristic Formations | Observed Structural Types | Dislocation, Color, Details, Observation Conditions. |
|---|---|---|---|---|
| 21 h 00 m | 1 | $h_{max}$=03°36'<br>$A$=163°<br>Extent:<br>$A$=141°, $h$=4°48'<br>$A$=218°24', $h$=00°36' | Veil | Maximum Brightness<br>Single Narrow Band |
| 21 h 30 m | 1 | $A$=150°36',$A$=190°12'<br>$h_{max}$=07°30' | I,II-a, II-b | Rapidly Changing Structure |
| 22 h 00 m | 1.5 | | II-a, III-a | Stars up to $m$=5-6 Seen in CZT |
| 22 h 10 m | 1.5 | Upper Boundary<br>$A$=187°05',$h$=30°29' | II-a, III-a, III-c | Absolutely Clear and Moonless Night |
| 22 h 20 m | 1.5 | $A$=151°,$h$=04°12'<br>$A$=159°46',$h$=04°48' | Narrow Band | Clearly Outlined Narrow Arcs of 2-5', Streams, Bands at $h$=4°12'-4°48' |
| 22 h 25 m | 2 | $A$=177°36',$h$=36°14'<br>$A$=185°46',$h$=30°29' | II-a,II-b, III-a | Bluish Noctilucent Clouds |
| 22 h 40 m | 2 | $A$=145°48',$h$=42°22' | III-a, III-b | Clearly Outlined, Wavy, Yellowish-Blue Structure |
| 22 h 45 m | 1 | $A$=169°12',$h$=54°29'<br>$A$=180°,$h$=48°29' | II-a, Patches | Single Bands Disappear, Waves Become Vague Patches |
| 22 h 55 m | 1.2 | $A$=169°12',$h$=60°<br>$A$=177°14',$h$=54°14' | II-a,II-b | Clouds Ascend, Bluish-White Color |
| 23 h 02 m | One blurred bluish-white band remained; it lost its structure rapidly | | | |
| 23 h 15 m | Clouds disappeared entirely | | | |

TABLE 2. /113

| Universal Time | Brightness (5-scale unit) | Azimuths and Heights of Characteristic Formations | Observed Structural Types | Dislocation, Color, Details, Observation Conditions. |
|---|---|---|---|---|
| 20 h 20 m | 1 | Maximum Brightness $A=171°, h=07°12'$ | II-a, III-b | Stars of $m=5$-6 Seen Through Clouds |
| 20 h 35 m | 1 | Measurements of a Bright Band $A=156°, h=04°12'$ $A=192°, h=06°$ | | Moving Toward the West |
| 20 h 50 m | 1 | $A=178°48', h=30°$ Upper Boundary, $h=54°$ | III-c, II-b | Unclear Veil |
| 21 h 04 m | 1.5 | | II-b, II-a, I | Veil Predominates |
| 21 h 12 m | 1 | | II-a, II-b | |
| 12 h 25 m | <1 | | II-a, III-a | Bluish-White Color |
| 21 h 30 m | <1 | Band Width of 5-7' $A=145°12', h=10°12'$ $A=165°58', h=10°48'$ | II-a, III-a I | Blurred, Unclear Structure |
| 21 h 45 m | Clouds ascended higher and lost their brightness, there were formations at the horizon, in the form of single bands arranged in levels. The bands shifted upward at a rate of 1-2' per second. | | | |
| 22 h 13 m | <1 | $A=193°12', h=21°$ | II-a, III-b | Very weak emission of a phosphorescent blue light |
| 22 h 15 m | <1 | | II-b, II-a I, II-a, III-b | Temperature of 14°. The II-b structure predominates along the horizon and above. Stars seen through clouds. |
| 22 h 23 m | <1 | Narrow Stream $A=171°58', h=08°10'$ | II-a, II-b | Blurred formations |
| 22 h 26 m | <1 | | I, II-a, III-a | |
| 22 h 37 m | 0.5 | | II-a | Single Bands Shift Upwards and Lose Brightness |
| 22 h 38 m | 0.5 | $A=185°24', h=11°11'$ Upper Boundary | II-a, III-a | Clearly Outlined Bands, Ripple, Crests, Small Waves |
| 22 h 45 m | Clouds from a lower level floating up | | | |
| 22 h 50 m | Single narrow bands with border points remained $A=189°, h=09°$ $A=196°34', h=09°$ | | | |
| 22 h 58 m | Last bands of noctilucent clouds disappeared | | | |
| 23 h 06 m | Last signs of noctilucent clouds disappeared ("melted") momentarily | | | |

# OBSERVATIONS OF NOCTILUCENT CLOUDS AT RYAZAN IN 1962

Ye.Ye. Artemkin

*Abstract: The author discusses eight cases when noctilucent clouds were observed, in conjunction with observations of artificial Earth satellites, over Ryazan in 1962.*

The observations of noctilucent clouds at Ryazan were conducted in 1962 by this author from the observation area of the Optical Station, in conjunction with observations of artificial Earth satellites. As a result of the incidental observations of the twilight sky (together with observations of artificial Earth satellites), eight cases of appearances of noctilucent clouds were recorded. A brief description of the phenomena observed is given below. /114

On July 11-12, noctilucent clouds, in the form of single bands, were found at 2335. The brightness of the clouds, which was 1 at the beginning, increased gradually: at 2350, it reached 3. Subsequently, the brightness began to decrease, and folds and streams appeared in the structure. After 0030, there were single bright (scale 2.5) bands which gradually decreased in brightness down to 1.5 (at 0100). During this time, the clouds had a well developed structure, standing out against the background of the twilight sector in the form of individual steams, bands, and folds. After 0100, the streams began to lose their clearly outlined shape, rapidly decreasing in brightness and acquiring a wave-shaped blurred structure. The stars were seen very clearly through the clouds. At 0130, the last signs of single blurred bands disappeared, but a stream arose with a brightness up to 1.5 ($A$ = 200°, $h$ = 6°). This stream gradually became weaker and disappeared at 0207.

On June 18-19, noctilucent clouds were discovered at 2300 at the boundary of the twilight segment, at an altitude of 10-15°. These clouds were moving rapidly upward and toward the southwest. At an altitude of 20-25°, the clouds had a maximum brightness of 3 (at 000). Subsequently, they began to become weaker and seemed to melt at an altitude of 30-35°. There was no clearly outlined structure. The clouds resembled bands; after midnight, only single patches remained distinguishable until 0025. The stars were seen very clearly through the clouds.

On June 20, a single band with a brightness up to 2 was observed at an altitude of 30° at the boundary of the twilight sector at 2330. It disappeared shortly after midnight.

On July 1-2, noctilucent clouds in the form of crests, waves and bands with brightnesses of 2-3 were detected at 2240. The stars were seen very clearly through them. A small ripple was seen at an altitude of 12-30°. At 2325, a small dark cloud from a lower level was formed against the background of the noctilucent clouds; it disappeared within 5 minutes. During this time, the noctilucent clouds had a clearly outlined structure of waves, bands, and crests; /115
their brightness was greater than 4 at certain moments. Vortices, waves, folds, and a clearly distinguishable small ripple were visible along the edges of the principal field of noctilucent clouds. At 2350, the brightness of the clouds decreased to 3.5, and their shift toward the west was significant. At 0010, the clouds had a billowed structure, and sharp bands were observed. The clouds had lost a great deal of brightness by 0020. The central bright cloud moved rapidly toward the west and downward, toward the horizon, around 0045. At 0050, the brightness of the clouds at $A$ = 156°36' and $h$= 5°24' was greater than that of the surrounding bands. Single crests and waves were developing there. The principal mass of the clouds had disappeared beyond the horizon by that time. The brightness contrast in the northwest increased with an increase of the twilight segment: the brightness of the clouds there became greater, in comparison to their principal mass. At 0130, the brightness of the clouds was less than 1, the structure was barely visible to the naked eye, and only single streams were visible in the commander's zenith telescope (CZT). A field of crests was seen in the CZT for $A$ = 138° and $h$ = 4°48' in the sky which was growing light, and clearly outlined bands, among which there were blurred bands, could be distinguished. The clouds were clearly distinguishable in the CZT, in the form of phosphorescent white bands, against the background of the twilight sky. At 0144, the twilight segment became very light, and the brightness of the clouds was less than 1. at 0215, the last signs of noctilucent clouds disappeared.

On July 4, cellular waves (like balls of cotton) were detected at the horizon at 0155; their brightness was not determined. At 0155, the clouds had the structure of bands, patches and waves whose brightness of 1-2 rapidly decreased. At 0200, the clear sky was preserved only in the twilight segment: clouds from a lower level were floating in from the south. At 0205, the structure of the clouds was less clear, and their brightness of about 1 also decreased greatly. By 0220, the clouds had become much fainter: single bands were found only with the aid of binoculars. The decrease of the brightness and the disappearance of clouds started noticeably from above and from the northeast. At 0230, the entire sky was already covered with cumulus clouds; on the other hand, it is more probable that the noctilucent clouds had disappeared between 0220 and 0230, and were not covered by clouds of a lower level.

On July 4, a weak luminous streak was seen at 2230, almost at the edge of the twilight segment. At 2320, the twilight segment was covered with clouds at a lower layer, but we could find no signs of noctilucent clouds at 0000, when the sky was entirely clear.

On August 5, noctilucent clouds in the form of wrinkled formations with a non-homogeneous upper border of a luminescent color were detected at the west at 2300. Their brightness was evaluated at 2. The clouds shifted toward the southwest and their wrinkles /116 smoothed out. They lost their structure, and rapidly took on the appearance of a veil. Some of the wrinkles fanned out from the central cloud. The height of the clouds above the horizon did not exceed 10-15°. The stars were seen very clearly through them. The clouds disappeared by 2330.

O.G. Bogdanov, N.V. Petrun'kin and P.D. Romadin observed these appearances.

On October 5 (!), the sky was illuminated from 2307 to 2318: a clear band of a white veil was seen at the north, where there were no city lights and where there could be no preliminary illumination. This could be a rare appearance of the visibility of noctilucent clouds in the month of October.

# OBSERVATIONS OF NOCTILUCENT CLOUDS AT TALLIN IN THE SUMMER OF 1962

C.I. Villmann

*ABSTRACT: The noctilucent clouds which were observed over Tallin in the summer of 1962 are described in this article.*

The Estonian division of the All-Union Astronomical and Geodetic Society, together with the Tallin Astronomical Observatory, organized surveying observations of the twilight sky and noctilucent clouds at Tallin in 1962. These surveys were the continuation of observations according to the IGY program begun in 1957. /116

In 1962, the observations were begun on May 15 and ended on September 1. On the whole, the observations included 100 nights and 410 hours. Noctilucent clouds were observed 6 times. Certain characteristics of these appearances are given in the table.

The duration of these appearances of noctilucent clouds was 4.3% of the total amount of surveying time. However, we should mention that this frequency of appearance of noctilucent clouds is the actual one, since the meteorological conditions for the surveying were very disadvantageous during the summer of 1962.

The twilight sky was clear (A and B according to [1]) only 11.4 of the entire time of the observations.

During the remaining time, the twilight segment was completely or partially covered with different types of tropospheric clouds (C,D, and E according to [1]).

## REFERENCES /117

1. Instruktsiya dlya nablyudeniy serebristykh oblakov (Instructions for Observations of Noctilucent Clouds). Izdat. Akad. Nauk S.S.S.R., 1957

TABLE

| No. | Date | Local Time | Brightness According to [1] |
|---|---|---|---|
| 1 | 7-8 June | 23 h 08 m -01 h 08 m | 2 |
| 2 | 17-18 June | 22 18 -01 23 | 1 |
| 3 | 2-3 July | 22 38 -01 48 | 2 |
| 4 | 19-20 July | 22 08 -01 23 | 3 |
| 5 | 28-29 July | 00 08 -01 38 | 2 |
| 6 | 29-30 July | 22 38 -02 50 | 3 |

| No. | Morphological Structure According to [1] | Direction of Movement of Cloud Field | Horizontal Coordinates of the Sun | |
|---|---|---|---|---|
| | | | *h* | *A* |
| 1 | I,II-a,b,III-b,c | NNW | 07°07′—06°42′ | 353°13′—08°28′ |
| 2 | I,II-a,b,III-a,b,IV-a | NW | 04 39 —05 27 | 347 23 —10 32 |
| 3 | I,II-a,b,III-a,b,IV-a,b | SE | 06 02 —04 26 | 350 09 —13 52 |
| 4 | I,II-a,b,III-a,b,IV-a,b | SW | 06 54 —07 46 | 346 46 —11 13 |
| 5 | I,II-a,III-b | S | 11 37 —08 50 | 03 41 —13 06 |
| 6 | I,II-a,b,III-a,b,IV-b | S | 10 22 —04 04 | 350 20 —20 49 |

# OBSERVATIONS OF NOCTILUCENT CLOUDS IN THE LATVIAN S.S.R. IN 1962

M.A. Dirikis and E. Ts. Mukins

*ABSTRACT: The noctilucent clouds observed over the Latvian S.S.R. in 1962 (at Riga and Sigulda) are described in this article.*

The photographic observations of noctilucent clouds by the Latvian division of the All-Union Astronomical and Geodetic Society /117 were conducted in 1962 at two sites, Riga and Sigulda. The observation sites were the same as in 1961 [1].

The data referring to the noctilucent clouds are given below (see the following table).

The following participated in the observations: at Riga, /119 S. Frantsman (Yevdokimenko), A. Krastynya, Yu. Frantsman, Z. Luse (Strautman) and D. Vaynberg; at Sigulda, M. Veyken, A. Plotkins, R. Vitolniyeks, L. Dirike, M. Dirikis, E. Mukins, and a group of first-form students of the Sigulda High School.

## REFERENCES

1. Frantsman, Yu.: Tsirkulyar VAGO (Circular of the All-Union Astronomical and Geodetic Society), No. 5, Moscow, 1962, p. 26.

| No. | Date, 1961 | Time | Brightness of clouds | Components of Twilight Sector | Negative Elevation of Sun | No. of Photographs Obtained |
|---|---|---|---|---|---|---|
| | | | **Riga** | | | |
| 1 | 19—20 June | 0 h 30 m — 2 h 15 m | 1 | A | 8°,6—9°,4 | — |
| 2 | 1—2 July | 0 00 — 3 30 | 1—5—2 | B | 5,4—9,6 | — |
| 3 | 2—3 July | 2 15 — 3 30 | 3—4—1 | B-A | 5,5—9,1 | 8 |
| 4 | 8—9 July | 2 20 — 2 45 | 1 | B | 8,6—9,4 | 7 |
| 5 | 19—20 July | 0 15 — 2 00 | 1—3—1 | A | 10,6—12,0 | — |
| | | | **Sigulda** | | | |
| 1 | 1—2 July | 0 00 — 3 15 | 3—5—1 | B | 6,4—9,7 | 70 |
| 2 | 5—6 July | 1 45 — 2 00 | 1 | B | 9,7—9,9 | 7 |
| 3 | 8—9 July | 1 15 — 3 35 | 2—1 | B | 6,2—10,4 | 26 |
| 4 | 19—20 July | 23 44 — 3 45 | 2—4—1 | B-A | 6,8—12,0 | 45 |
| 5 | 14—15 Aug | 21 55 —22 40 | 3—1 | A | 6,4—10,8 | 8 |

# OBSERVATIONS OF NOCTILUCENT CLOUDS IN ESTONIA DURING THE SUMMER OF 1963

Kh.Ya. Turbal

*ABSTRACT: The eleven cases of noctilucent clouds observed over Estonia during the summer of 1963 are discussed in this article. The author concludes that noctilucent clouds are usually very bright, and are visible rather frequently during the summer months.*

In 1963, the Tallin Astronomical Observatory of the Institute of Physics and Astronomy of the Academy of Sciences of the Estonian S.S.R., and the Estonian Division of the All-Union Astronomical and Geodetic Society were continuing the observations of noctilucent clouds begun in 1957 (see, for example, [1-5]). /119

The surveying observations of the twilight sky and noctilucent clouds at Tallin and Nymma were begun on June 25 and ended on September 1.

In all, the observations lasted 67 nights and 323 hours. L. Calve, Ya. Lokk, Yu. Tarmak and Kh. Turbal were the observers.

In addition to conducting the survey observations (according to the IGY program [6], the principal task was to obtain photographs with the aid of a three-lens camera and an aerial camera (AFA-IM) in order to determine the polarization and photometric properties of the light of noctilucent clouds as well as the dynamics of the noctilucent clouds.

The characteristic distribution of the twilight interval by different types of recording and meteorological conditions during the period of the observations is given in Table 1.

Noctilucent clouds were recorded 11 times during the period of the survey. Certain characteristics of the noctilucent clouds are given in Table 2.

Yu. Kestlane, a former laboratory technician at the Tallin Astronomical Observatory, conducted observations in Kingiseppa on his own initiative.

TABLE 1. DISTRIBUTION OF TWILIGHT INTERVAL BY VARIOUS TYPES OF RECORDING AND METEOROLOGICAL CONDITIONS DURING THE PERIOD WHEN NOCTILUCENT CLOUDS WERE OBSERVED AT TALLIN -NYMMA IN 1963

| period of observations | time | | yes | | | No! | | No | | No? | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | nights | hours | night | hrs | % | hours | % | hours | % | hours | % |
| June | 5 | 11,25 | — | — | | — | — | 2,25 | 20,0 | 6,75 | 60,0 |
| July | 31 | 119,75 | 8 | 18,00 | 15,00 | 2,25 | 1,9 | 18,75 | 15,7 | 51,50 | 43,0 |
| August | 31 | 192,25 | 3 | 3,75 | 1,9 | — | — | 21,00 | 10,9 | 62,75 | 32,7 |
| total nights | 67 | | 11 | | | — | | — | | — | |
| total hours . . . | 323,25 | | 21,75 | | | 2,25 | | 42,00 | | 121,00 | |
| % . . . . . . . | | | 6,7 | | | 0,7 | | 13,0 | | 37,4 | |

| period of observations | — | | A | | B | | C | | D | | E | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | hours | % | hours | % | hours | % | hours | % | hours | % | hours | % |
| June . . . | 2,25 | 20,0 | — | — | 3,75 | 33,3 | 5,25 | 46,7 | — | — | 2,25 | 20,0 |
| July . . . | 29,25 | 24,4 | 16,00 | 13,4 | 14,00 | 11,7 | 43,75 | 36,5 | 16,75 | 14,0 | 29,25 | 24,4 |
| August . . . | 104,75 | 54,5 | 5,75 | 3,0 | 23,25 | 12,1 | 52,50 | 27,3 | 6,00 | 3,1 | 104,75 | 54,5 |
| total nights . . . | — | | — | | — | | — | | — | | — | |
| total hours . . . | 136,25 | | 21,75 | | 41,00 | | 101,50 | | 22,75 | | 136,25 | |
| % . . . . . . . . . | 42,2 | | 6,7 | | 12,7 | | 31,4 | | 7,0 | | 42,2 | |

TABLE 2. CERTAIN CHARACTERISTICS OF THE NOCTILUCENT CLOUDS AND TWILIGHT SECTOR RECORDED DURING THE OBSERVATIONS AT TALLIN-NYMMA IN 1963

| Date | time (standard) | | brightness | morphological types | negative elevation of Sun | azimuth of Sun | cloudiness of twilight sky |
|---|---|---|---|---|---|---|---|
| | beginning | end | | | | | |
| 30.VI– 1.VII | 01 h 00 m | 02 h 30 m | 1—2 | I, II-*a*, II-б IV-б | 7°16′— 6°20′ | 174°12′—194°59′ | C |
| 1 — 2 | 00 15 | 02 45 | 1—2 | I, II-*a*, II-б III-б | 6 14 — 7 24 | 163 45 —184 35 | A |
| 2 — 3 | 23 30 | 03 00 | 1—4 | II-*a*, II-б IV-*a* | 4 11 — 5 17 | 153 25 —201 51 | C, B |
| 4 — 5 | 00 15 | 02 15 | 1—4 | II-*a*, II-b III-*a*, III-b | 6 24 — 7 07 | 163 37 —191 23 | C |
| 15 —16 | 01 15 | 02 45 | 1—4 | I, II-*a*, II-b | 9 03 — 7 35 | 177 03 —197 53 | B |
| 20 —21 | 00 30 | 03 00 | 1—3 | I, II-*a* III-c | 9 01 — 7 46 | 193 41 —201 49 | C, E |
| 23 —24 | 23 30 | 03 30 | 1—5 | I, II-*a*, II-b III-*a*, III-b IV-*a*, IV-b IV-c | 6 56 — 6 42 | 152 16 —208 55 | B |
| 26 —27 | 01 00 | 02 00 | 1—2 | II-*a* | 11 08 —11 07 | 173 11 —187 55 | C, D |
| 4 — 5 VIII | 23 45 | 00 30 | 1—3 | II-*a* | 10 21 —12 16 | 155 06 —165 51 | C, E |
| 9 —10 | 01 30 | 04 15 | 1—4 | I, II-*a*, II-b III-*a* | 14 45 — 7 54 | 180 40 —219 08 | C |
| 20 —21 | 04 27 | 04 38 | 1 | II-*a* | 9 20 — 8 26 | 225 09 —228 21 | C, B |

He noticed noctilucent clouds 5 times: on July 2-3, July 15-16, July 20-21, and July 23-24. It is interesting to note that he observed noctilucent clouds on July 2-3 at 0400, for a negative elevation of the Sun of 2°11', and on July 23-24, at 0420, for a negative elevation of the Sun of 3°37'. /122

As we can see from Tables 1 and 2, the greatest number of noctilucent clouds appeared in July (8 times); they appeared 3 times in August.

There were no noctilucent clouds observed at the end of June.

If we compare the noctilucent clouds recorded in Tallin during the preceding year with those recorded in the summer of 1963, we can find the following circumstances:

(1) Noctilucent clouds were visible rather often. They existed for 6.7% of the entire time of the patrol observations (the percentage for 1957 was 2.7; for 1958, 0.9; for 1959, 6.3; for 1961, also 6.7%).

(2) In many cases, noctilucent clouds have rather high brightness.

(3) Noctilucent clouds are usually visible around the horizon and at an average height above the horizon, but they were visible around the zenith on July 2-3.

In conclusion, I consider it my duty to express my appreciation to L. Calve, a laboratory technician at the Tallin Astronomical Observatory, to Ya.Lokk and Yu. Tarmak, members of the All-Union Astronomical and Geodetic Society, for their conscientious work on the tasks assigned, and to Yu. Kestlane, for contributing his materials to this discussion.

## REFERENCES

1. Villmann, C.I.: O nablyudenii serebristykh oblakov v Talline v 1957-1958 (Observations of Noctilucent Clouds at Tallin in 1957-1958), in: Trudy soveshchaniya po serebristym oblakam (Works of a Conference on Noctilucent Clouds), Vol. I Tartu, 1959, pp. 41-51.
2. Villmann, C. and U.J. Veltmann: Helkivate oopilvede Vaatlustest Tallinnas ja Tartus 1957. (Observations of Noctilucent Clouds at Tallin and Tartu in 1957 and Subsequent Years).
3. Villmann, C.I.: Nablyudeniya serebristykh oblakov v Estonii letom 1959 g (Observations of Noctilucent Clouds in Estonia during the Summer of 1959), in: Trudy soveshchaniya po serebristym oblakam (Works of a Study of Noctilucent Clouds), Riga, 1961, pp. 181-190.

4. Villmann, C.I.: O fotograficheskoy fotometrii, polyarimetrii i kolorimetrii serebristykh oblakov (Photographic Photometry, Polarimetry, and Colorimetry of Noctilucent Clouds), in: Trudy VI soveshchaniya po serebristym oblakam (Works of the Sixth Conference on Noctilucent Clouds). Riga, 1961, pp. 25-34.
5. Villmann, C.I.: Nablyudeniya serebristykh oblakov v severo-zapadnoy chasti Atlantiki i na territorii Estonii v 1961 godu (Observations of Noctilucent Clouds in the Northwestern Atlantic and in the Territory of Estonia in 1961), in: Trudy soveshchaniya po serebristym oblakam (Works of a Conference on Noctilucent Clouds), Vol. III. Tallin, 1962, pp. 169-179.
6. Instruktsiya dlya nablyudeniy serebristykh oblakov. Mezhdunarodnyy geofizicheskiy god (Instructions for Observations of Noctilucent Clouds. International Geophysical Year). Izdat. Akad. Nauk S.S.S.R., 1957.

# CALCULATING THE COORDINATES OF NOCTILUCENT CLOUDS ON THE BESM-2

S.V. Frantsman (Yevdokimenko) and Yu.L. Frantsman

*ABSTRACT: The results of the first calculations on the BESM-2 (a high-speed electronic computer) for the altitudes and geographic coordinates of noctilucent clouds are presented in this article. Descriptions are given for the formulas used in the program of the machine. The author shows the accuracy of the results obtained, and their significance in introducing new and more complete data for the study of noctilucent clouds.*

The altitudes and geographic coordinates of noctilucent clouds /123 and the velocity and direction of their movement can be determined by simultaneous photographs made from two or more observation sites. During the IGY and the IGU, as well as the subsequent period, the Latvian division of the All-Union Astronomical and Geodetic Society obtained a large number of reference photographs of noctilucent clouds suitable for analysis. In 1959, M.A. Dirikis and Yu.L. Frantsman [1] proposed a simplified method for determining the altitudes and geographic coordinates of noctilucent clouds. The simplications were achieved primarily by an introduction of orthogonal equatorial coordinates. This method can involve the use of photographs made by different types of cameras whose optical axes can be non-parallel (in contrast, for example, to the method proposed by M.I. Burov [2]). The first results of the calculations for the altitudes of noctilucent clouds by this method were published in [1] and [3].

At the present, we can consider unknown the average altitude of the layer in which noctilucent clouds appear. On the other hand, we still do not know the thickness of the layer of noctilucent clouds, or if there are two or more layers.

The study of the movement of noctilucent clouds is of great interest. It is well known that the movements are primarily in a western direction; however, this is the movement of the entire mass of clouds as a whole. The smaller morphological formations make complex wave-shaped, vortical and other movements [4,5]. Having studied the movement of noctilucent clouds, we can obtain data concerning the wind velocity, and the nature and direction of the movement of layers of the atmosphere at corresponding altitudes. In order to study the kinematics of noctilucent clouds, it is necessary to analyze a very large quantity of observational materials. We have attempted to add to these materials, so that the analysis of observations can possibly become less time-consuming. For this purpose, we constructed a program for calculating the coordinates of noctilucent clouds on a high-speed electronic computer (BESM-2). The results of the first calculations on the BESM-2 for the altitudes and the geographic coordinates of noctilucent clouds are presented in this article.

## Formulas for Determining the Altitudes and Geographic Coordinates of Noctilucent Clouds

The coordinates of noctilucent clouds were calculated by introducing orthogonal equatorial coordinates (Fig. 1). We will assume that simultaneous photographs of noctilucent clouds with general details were obtained from two observation sites *A* and *B*. We will call one of these details *C*. An equatorial geocentric system of coordinates is constructed from the origin at the center of the Earth, the *X*-axis is directed toward the point where the Greenwich meridian and the equator intersect, the *Y*-axis is directed toward the point of the equator with a longitude of 90°E, and the *Z*-axis is directed toward the North Pole of the Earth $P_N$. /124 The coordinates of the observation sites in this system are equal to $x_A$, $y_A$, $z_A$, and $x_B$, $y_B$, and $z_B$, respectively. Now we can introduce the topocentric systems of coordinates $X_A$, $Y_A$, $Z_A$ and $X_B$, $Y_B$, $Z_B$, with axes parallel to the *X*, *Y* and *Z* axes, but with origin of the coordinates at the points *A* and *B*, respectively

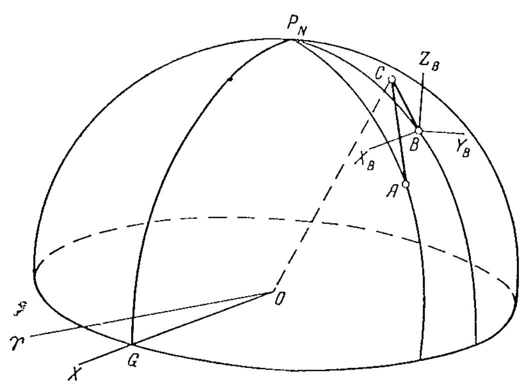


Fig. 1. System of Rectangular Equatorial Coordinates

(Figure 1 shows only the system of coordinates with an origin at *B*). All the values involving point *A* will be designated by one apostrophe, and all those involving point *B* will be designated by two. For the point *C* in the noctilucent cloud in the photographs obtained at *A* and *B*, we will determine the equatorial coordinates by the methods of photographic astrometry, i.e., we will determine the ascension α and the declination δ. The topocentric coordinates of point *C* are the following:

$$x' = \rho' \cos \delta' \cos (\alpha' - S);$$
$$y' = \rho' \cos \delta' \sin (\alpha' - S);$$
$$z' = \rho' \sin \delta';$$
$$x'' = \rho'' \cos \delta'' \cos (\alpha'' - S);$$
$$y'' = \rho'' \cos \delta'' \sin (\alpha'' - S);$$
$$z'' = \rho'' \sin \delta''.$$

Here, $S$ is the angle $\gamma OX$ equal to Greenwich stellar time at the moment of the observation. The unknowns on the right-hand side of the equations are the distances $\rho'$ and $\rho''$ from the observation sites to point $C$.

Let us abbreviate the unknown values in the following way: /125

$$X' = \cos \delta' \cos (\alpha' - S);$$
$$Y' = \cos \delta' \sin (\alpha' - S);$$
$$Z' = \sin \delta';$$

$$X'' = \cos \delta'' \cos (\alpha'' - S);$$
$$Y'' = \cos \delta'' \sin (\alpha'' - S);$$
$$Z'' = \sin \delta''.$$

The system of equations for determining the coordinates of the point $C$ ($x_C$, $y_C$, $z_C$) in the geocentric system of coordinates can now be written in the following way:

$$x_C = x_A + \rho' X';$$
$$y_C = y_A + \rho' Y';$$
$$z_C = z_A + \rho' Z';$$

$$x_C = x_B + \rho'' X'';$$
$$y_C = y_B + \rho'' Y'';$$
$$z_C = z_B + \rho'' Z''.$$

We have six equations with five unknowns ($x_C$, $y_C$, $z_C$, $\rho'$ and $\rho''$); thus, the system can be solved by the method of least squares.

In order to find the height $h$ above sea-level and the geographic coordinates (latitude $\phi$ and longitude $\lambda$) for $C$, we will write the equation for the line which passes through the origin of the geocentric system of coordinates and $C$, in the following way:

$$\frac{x}{x_C} = \frac{y}{y_C} = \frac{z}{z_C}.$$

Considering the Earth's surface to be an ellipsoid with two equal axes, we can use the following equation for an ellipsoid:

$$x^2 + y^2 + \frac{z^2}{b^2} = 1,$$

where $b$ is the minor semiaxis of the ellipsoid in units of the equatorial radius of the Earth. Having solved these equations jointly, and having introduced the value

$$K = \frac{b}{\sqrt{b^2 (x_C^2 + y_C^2) + z_C^2}},$$

the coordinates $x_{in}$, $y_{in}$, and $z_{in}$ for the point where the line intersects with the ellipsoid in the orthogonal equatorial geocentric cyctem of coordinates can be obtained in the following way: /126

$$x_{in} = x_C K;$$
$$y_{in} = y_C K;$$
$$z_{in} = z_C K.$$

The geocentric latitude $\phi'$ of $C$ is the following:

$$\varphi' = \arcsin \frac{z_{in}}{R},$$

where

$$R = \sqrt{x_{in}^2 + y_{in}^2 + z_{in}^2}$$

while the longitude is

$$\lambda = \operatorname{arc\,tg} \frac{y_{in}}{x_{in}}.$$

In order to convert the geocentric latitude $\phi'$ into the geographic one $\phi$, we will use the following formula:

$$\operatorname{ctg} \varphi = (0{,}993307 + 10^{-6}\, 0{,}0011 h_0) \operatorname{ctg} \varphi'.$$

We will consider the height $h_0$ equal to the average height of the noctilucent clouds, i.e., 82 km.

If we call the distance from the origin of the coordinates to $C\rho_c$, the height $h$ of the point in the noctilucent clouds is the following :

$$h = \rho_c - R,$$

where

$$\rho_C = \sqrt{x_C^2 + y_C^2 + z_C^2}\,.$$

The error allowed in calculating the height, as a result of the fact that the line passes through the center of the Earth and the point $C$ does not coincide with the perpendicular plotted from $C$ to the surface of the Earth, is so small (on the order of 20 m) that it may be disregarded.

## Determining the Equatorial Coordinates of Noctilucent Clouds

The orthogonal coordinates of the images of the details in the noctilucent clouds and the reference stars on the film were measured on a universal measuring microscope (U IM-21); this instrument belonged to the Astronomical Observatory of the Latvian Government. The measurements were also conducted on a measuring Zeiss microscope which had a similar design and belonged to the Physics Institute of the Academy of Sciences of the Latvian S.S. R /127

The measured orthogonal coordinates of the points in the noctilucent clouds were converted into equatorial coordinates by the Turner method, and the terms were considered up to the second order, inclusive. For each film, it was necessary to solve two systems of equations with six unknowns, i.e. :

$$\xi_i = ax_i + by_i + c + kx_i^2 + lx_i y_i + my_i^2;$$

$$\eta_i = dx_i + ey_i + f + px_i^2 + qx_i y_i + ry_i^2,$$

where $a, b, c, k, l, m, d, e, f, p, q$ and $r$ are the constants to be determined; $x_i$ and $y_i$ are the orthogonal coordinates of the image of the star whose number is $i$; $\xi_i$ and $\eta_i$ are the ideal coordinates of the same star. In considering the terms of the second order, the effect of the differential refraction is decreased; in our case, it should reach a substantial value. The effect of certain other factors is also decreased. The systems of equations were solved by the method of least squares.

In order to determine the equatorial spherical coordinates $\alpha$ and $\delta$ of the noctilucent clouds, it is necessary to know the equatorial coordinates of the optical center in the photograph. We can use the geometric center of the photograph as an approximation of the optical center, since the corresponding error in determining $\alpha$ and $\delta$ of these points is very small. We completed calculations which showed that even a change in the rectilinear coordinates of the optical center by 10 mm changes the equatorial coordinates of the measured objective on the average by 0.5″.

Thus, since the coordinates of the optical center are sufficiently approximate, we can assume that the equatorial system of coordinates is projected to the film, as an orthogonal system on a plane in order to determine $\alpha$ and $\delta$ of the optical center in a small field around the center of the film. To determine the equatorial coordinates of the optical center according to the measured orthogonal coordinates, we can now use the general formulas for converting rectangular coordinates into planes. For this purpose, we will take two reference stars from among those which will be used later to determine the equatorial coordinates of the points in the noctilucent clouds.

## Program

In the program for the calculation of the coordinates of noctilucent clouds on the BESM-2, it was stipulated that the problems of two pairs of photographs be solved each time. Punched cards were fed in and results printed out after each minute of machine time.

The block-diagram of the program for the calculation of altitudes and geographic coordinates of noctilucent clouds on the BESM-2 is shown in Figure 2. /128

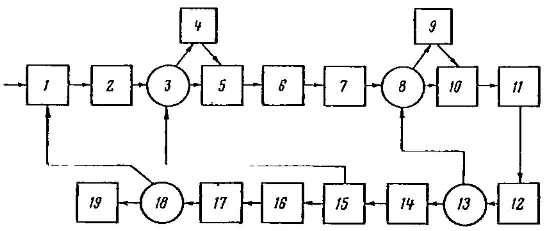


Fig. 2. Block-Diagram of the Program for Calculating the Altitudes and Geographic Coordinates of Noctilucent Clouds on the BESM-2.

Block 1 introduces the following:

(1) The equatorial coordinates of the reference stars for a pair of negatives,

(2) The measured orthogonal coordinates of the same reference stars,

(3) The measured orthogonal coordinates of points in the field of noctilucent clouds,

(4) The coordinates of both observation sites in the equatorial geocentric system of coordinates,

(5) The orthogonal coordinates of the optical center for each negative,

(6) The Greenwich sidereal time at midnight and the universal time at the moment of the observation,

(7) Various auxiliary values (the number of reference stars for each film, the number of reference stars used in determining the equatorial coordinates of the optical center, etc.).

The calculations of the equatorial coordinates of the points in the noctilucent clouds followed the same course for each negative. In order to use the same part of the program for calculations of the same type, a special number showing the sequence of films was introduced in Block 2 (in our case, the number 0 was used for the film taken at Sigulda, and the number 1 was used for that taken at Baldona).

Block 3 checks which film was calculated (the 0 films were transferred to Block 5, and the 1 films were transferred to Block 4).

Block 4 regulates repeated calculations for the first film.

Block 5 determines the equatorial coordinates of the optical center of the film according to two reference stars.

Block 6 calculates the ideal coordinates of the reference stars. /129

In constructing the equations for determining the constants, it was necessary to distinguish the systems of equations for $\xi$ and $\eta$. Block 7 establishes special signs for these equations.

Block 8 checks which system was involved in the calculations (for $\xi$ or $\eta$; in the first case, the controls were transferred to Block 10, in the second case, they were transferred to Block 9).

Block 9 regulates the corresponding controls for constructing the system for $\eta$.

Block 10 constructs the system of normal equations.

Block 11 solves the system of normal equations.

Block 12 determines the ideal coordinates of the points in the noctilucent clouds according to the constants of the film, which have now been determined.

Block 13 checks whether or not the ideal coordinates of the points $\eta$ in the noctilucent clouds have already been calculated, or if only $\xi$ was calculated (in the first case, the control is transferred to Block 14, and in the second case, to Block 8).

Block 14 finds the equatorial coordinates for the points in the noctilucent clouds according to the ideal coordinates.

Block 15 checks whether or not calculations were made for both films, or only for one (in the first case, the control transfers to Block 16, and in the second case, to Block 3).

Block 16 determines the altitudes of the noctilucent clouds and their geographic coordinates.

Block 17 prints out the results.

Since the program was designed for calculating two pairs of photographs, Block 18 checks to see if both pairs have been calculated (if only one pair has been calculated, the controls are transferred to Block 1; if calculations have been made for both pairs, then the controls are transferred to Block 19).

Block 19 stops the machine.

Moreover, there is an additional block which calculates the spherical coordinates of the reference stars according to the constants obtained, after which the calculated coordinates are compared to those given in the catalogue. The corresponding differences for each ascension and declination are printed out for both photographs. This aids in finding gross errors in the measurements and identification of the stars. We will discuss this later in more detail.

The blocks which construct and solve the systems of normal equations were written in a way similar to that in the program for determining the first approximations of the geocentric coordinates of an artificial earth satellite, which was constructed by the Astronomical Society of the Latvian Government. The terms of the normal equations were constructed without the aid of stored conditional equations, but with the aid of the initial data. The system of normal equations was solved by the Gauss method, i.e., by changing the matrix of the coefficients for the unknowns to a unit matrix by dividing its elements into the maximum possible number of sections for each stage.

The following results are printed out: the film for which the twelve constants were given, the differences between the calculated equatorial coordinates of the reference stars and those given in the catalogue, the geographic coordinates of the noctilucent clouds, and their altitudes. /130

## Analysis of the Accuracy in Determining the Coordinates of the Noctilucent Clouds

The errors which substantially affect the results in determining the coordinates of noctilucent clouds can be divided into the following three categories:

(1) The errors in measuring the orthogonal coordinates of the stars and noctilucent clouds. The images of the stars on the negative were clear, and it was rather easy to guide the cross hairs of the measuring microscope toward such an objective. The accuracy of this aiming was evaluated by measuring the images of the stars with upright and inverted positions of the record, which was made specially for testing the AFA-IM aerial camera. The sum of the scale readings for the measuring microscope should be constant for all the stars in each position. We measured 23 images of stars; the measurement error for the $X$-axis was equal to $\pm 0.022$ mm, for the $Y$-axis, $\pm 0.020$ mm (here, and subsequently, we are using the mean square error). A value of 0.02 mm on the film corresponds to an arc of $17''$ in the celestial sphere.

It was more difficult to measure the images of the details (which are usually rather blurred) in the noctilucent clouds, since the images themselves were not clear, and also since the noctilucent clouds moved and the images shifted on the film during the exposure time. Thus, the measurement accuracy depends on many factors (the nature of the details, the rate of cloud movement, and the exposure time). It is difficult to determine the measurement accuracy, and it must be approximated each time. Moreover, a measured detail in photographs of the noctilucent clouds taken at two observation sites can have a different appearance; thus, when we are analyzing a pair of photographs, we are not actually measuring the same point in each one. Having conducted several measurements, and finding the same points when the film is in an upright and inverted position, we can evaluate the error in measuring the orthogonal coordinates in the details of the noctilucent clouds: it varies from $\pm 0.05$ and $\pm 0.2$ mm. This is much greater than the errors found in measuring the images of the stars; it is so much greater that the effect of the errors in measuring individual stars decreases when we consider the large number of reference stars. In order to determine how the inaccuracies in measuring the orthogonal coordinates of the points in the noctilucent clouds affect the calculations for their altitudes, the orthogonal coordinates of the images of the noctilucent clouds were changed by 0.1 mm in the program for calculations. With such measurements, one of the orthogonal coordinates of the altitude changed, on the average, by $\pm 0.6$ km. /131

(2) The differential refraction, distortion, differential aberration (to a lesser degree), the inclination of the film, and other factors affect the correctness of the results. The differential refraction is particularly important, since the measured objectives are at a relatively great height above the horizon. On the other hand, the corrections which should be introduced for the effect of these factors can be either linear or in the form of an ordered series, depending on the measured coordinates. Since we will be using quadratic terms in the expansion, these effects (except the distortion) can be considered. We studied the distortion of the objective for one of the cameras. A relatively great distortion did not greatly affect the correctness of the calculation results, in our case. Thus, if we take a star at a distance of 10° from the center of the negative, the correction for the distortion is equal to 0.016 mm in all, which is roughly on the order of one for the measurement accuracy of the images of the stars.

In order to be more convinced that all these errors are small, we calculated the coordinates ($\alpha$ and $\delta$) of the stars which were not included among the reference stars, and we compared them to the coordinates given in the catalogue. The average quadratic deviation for $\alpha$ was equal to $\pm 25''$, and to $\pm 14''$ for $\delta$. Actually, these errors do not exceed the measurement accuracies for the orthogonal coordinates of the stars. In another case, the reference stars were taken from the center of a simulated negative for one direction and the calculated ones for another direction. These calculated deviations were equal to $\pm 67''$ for $\alpha$ and $\pm 39''$ for $\delta$. We can conclude that the accuracy was completely satisfactory, since the errors in measuring the orthogonal coordinates of the images of noctilucent clouds were incomparably greater.

(3) Gross errors are often found in analyzing photographs of noctilucent clouds. For example, there can be errors in identifying the stars, reading the numbers on the scale of the measuring microscope, punching out the data on the punched cards, etc. This should have a great effect on the results. Therefore, we decided to find ways to avoid such errors. As we have already mentioned, there is a block in the program which calculates the coordinates $\alpha$ and $\delta$ of the reference stars, and the differences between the accepted and the calculated coordinates are printed out. If any

gross error is permitted, it is usually found in these differences. This block was absolutely necessary, since these errors were detected in at least half of the pairs of negatives analyzed. In our case, they were excluded completely, and we could be more certain of the reality of the results obtained.

## Discussion of the Results Obtained

The following table gives the results of calculations for 68 geographic coordinates and altitudes of noctilucent clouds obtained for seven pairs of negatives which were photographed at Sigulda and Baldona on the night of July 14-15, 1959. The average altitude of the noctilucent clouds was equal to 83.4 km. This result was somewhat greater than the average values of the altitudes presented by C. Stormer (82.1 km) [6,7], M.I. Burov (82.5 km) [2] and others. /132

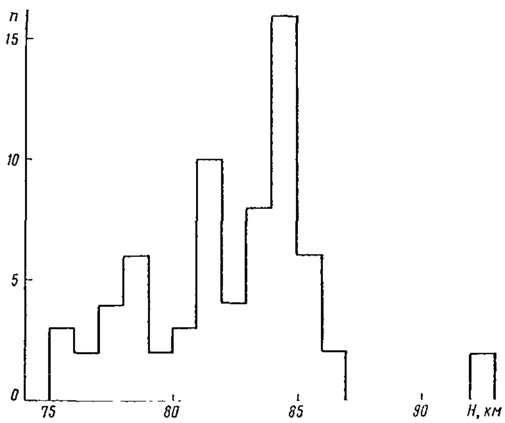


Fig. 3. Distribution of Noctilucent Clouds by Altitude (July 14-15, 1959, Sigulda-Baldona)

The diagram in Figure 3 gives the distribution of the number of points in noctilucent clouds by altitude. The maximum distribution is found at 84-85 km. There are two more maxima; this may indicate that there are several layers in noctilucent clouds. However, we cannot draw any definite conclusions, because of the relatively small number of measured altitudes. There is another feature of the diagram which is more reliable, as well as interesting: the slight increase on the part of the lower altitudes and the abrupt increase on the part of the higher altitudes. This could indicate that there is a sharp boundary above the layer in which noctilucent clouds can appear. Thus, there could be a change in some physical properties of the atmosphere on which the appearance of noctilucent clouds depends.

It is possible that the two abnormally great values for the altitudes (91 and 92 km) are errors, since there are many such details in the form of waves on the photograph, and the measured points may have been identified incorrectly, despite the fact that they belong to one detail in the cloud.

# COORDINATES AND ALTITUDES OF NOCTILUCENT CLOUDS

| No. | No. of photograph | Moscow time | No. of detail | altitude km | latitude φ | longitude λ |
|---|---|---|---|---|---|---|
| 1 | S816—B96 | 0 h 26 m | 1 | 84.3 | 59°.03 | 23°.29 |
| 2 | | | 2 | 84.6 | 59.10 | 23.39 |
| 3 | | | 3 | 83.1 | 58.91 | 23.72 |
| 4 | | | 4 | 83.6 | 59.18 | 23.62 |
| 5 | | | 5 | 85.8 | 59.40 | 23.31 |
| 6 | | | 6 | 84.4 | 59.36 | 23.38 |
| 7 | | | 7 | 82.2 | 59.18 | 23.64 |
| 8 | | | 8a | 84.6 | 59.47 | 23.50 |
| 9 | | | 8b | 84.5 | 59.47 | 23.50 |
| 10 | | | 9a | 84.4 | 59.45 | 23.57 |
| 11 | | | 9b | 84.4 | 59.45 | 23.57 |
| 12 | | | 10 | 83.2 | 59.24 | 23.80 |
| 13 | S817—B97 | 0 28 | 1 | 85.8 | 59.10 | 23.52 |
| 14 | | | 2a | 84.6 | 59.13 | 23.58 |
| 15 | | | 2b | 84.9 | 59.12 | 23.61 |
| 16 | | | 3 | 80.9 | 59.12 | 23.64 |
| 17 | | | 4 | 81.6 | 59.32 | 23.52 |
| 18 | | | 5 | 85.1 | 59.04 | 23.84 |
| 19 | | | 6 | 77.1 | 59.37 | 23.74 |
| 20 | | | 7a | 75.7 | 59.71 | 23.79 |
| 21 | | | 7b | 81.8 | 59.90 | 23.72 |
| 22 | | | 8 | 86.8 | 59.13 | 24.21 |
| 23 | | | 9 | 85.3 | 58.93 | 23.91 |
| 24 | S818—B98 | 0 30 | 1a | 81.3 | 59.88 | 25.47 |
| 25 | | | 1b | 80.8 | 59.89 | 25.46 |
| 26 | | | 2 | 84.9 | 60.60 | 25.87 |
| 27 | | | 3 | 84.4 | 60.50 | 25.89 |
| 28 | | | 4 | 86.3 | 60.79 | 26.02 |
| 29 | | | 5a | 79.3 | 61.42 | 26.13 |
| 30 | | | 5b | 83.7 | 61.69 | 26.42 |
| 31 | | | 5c | 80.1 | 61.59 | 26.30 |
| 32 | | | 5d | 84.5 | 61.74 | 26.48 |
| 33 | | | 6 | 81.6 | 61.21 | 26.62 |
| 34 | | | 7 | 82.0 | 60.49 | 27.32 |
| 35 | | | 8 | 84.4 | 60.44 | 27.40 |
| 36 | | | 9a | 83.4 | 60.44 | 27.52 |
| 37 | | | 9b | 85.5 | 60.44 | 27.52 |
| 38 | | | 10 | 82.6 | 60.53 | 27.59 |
| 39 | | | 11 | 84.5 | 60.36 | 27.75 |
| 40 | | | 12 | 82.5 | 60.41 | 27.18 |

| No. | No. of photograph | Moscow time | No. of detail | altitude km | latitude φ | longitude λ |
|---|---|---|---|---|---|---|
| 41 | S821—B100 | 0 h 36 m | 1 | 77.7 | 59.62 | 25.44 |
| 42 | | | 2 | 77.8 | 60.24 | 25.84 |
| 43 | | | 3 | 80.3 | 60.14 | 27.28 |
| 44 | | | 4 | 83.1 | 60°.17 | 27°.40 |
| 45 | | | 5 | 81.6 | 60.06 | 27.39 |
| 46 | S823—B101 | 0 40 | 1 | 81.4 | 59.99 | 25.52 |
| 47 | | | 2a | 76.1 | 59.89 | 25.58 |
| 48 | | | 2 b | 76.5 | 59.92 | 25.62 |
| 49 | | | 2 c | 78.5 | 60.02 | 25.67 |
| 50 | | | 3 | 78.9 | 60.01 | 25.69 |
| 51 | | | 4 | 83.4 | 60.29 | 25.84 |
| 52 | | | 5 | 75.0 | 60.08 | 25.82 |
| 53 | | | 6 | 75.7 | 59.58 | 26.24 |
| 54 | | | 7 | 78.7 | 59.78 | 26.41 |
| 55 | | | 8a | 92.8 | 60.18 | 26.99 |
| 56 | | | 8 b | 91.9 | 60.16 | 26.99 |
| 57 | | | 9 | 82.5 | 59.88 | 26.88 |
| 58 | | | 10 | 82.0 | 60.09 | 27.34 |
| 59 | | | 11a | 77.8 | 59.96 | 27.26 |
| 60 | | | 11b | 78.6 | 59.98 | 27.29 |
| 61 | | | 12 | 78.6 | 59.72 | 27.19 |
| 62 | S828 B105 | 0 50 | 1 | 84.1 | 59.97 | 22.02 |
| 63 | | | 2 | 84.9 | 60.20 | 22.19 |
| 64 | | | 3 | 85.7 | 61.23 | 22.11 |
| 65 | S831 B108 | 1 04 | 3 | 84.3 | 60.81 | 21.82 |
| 66 | | | 4 | 83.0 | 61.02 | 21.95 |
| 67 | | | 5 | 78.9 | 60.57 | 22.80 |
| 68 | | | 6 | 79.1 | 60.29 | 23.55 |

NOTE: The number of the detail in the noctilucent cloud is given in sequence in the first column; the number of the photographs of the corresponding pair is given in the second column; the Moscow Standard Time is given in the third column for the beginning of the exposure; the number of the detail in the same pair of photographs is given in the fourth; in the fifth, the altitude of the noctilucent cloud in kilometers; in the sixth and seventh, the geographic latitude and longitude (in degrees), respectively.

We could also say the same about the low altitudes of 75-76 km, although these cases are more realistic. Further studies are necessary in order to maintain definitely that noctilucent clouds can appear at such different altitudes (from 75 to 92 km). For other authors (for example, G. Witt [8]), the range of altitudes was much more narrow.

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## REFERENCES

1. Dirikis, M.A. and Yu.L. Frantsman: Trudy VI soveshchaniya po serebristym oblakam (Works of the Sixth Conference on Noctilucent Clouds). Riga, 1961.
2. Burov, M.I.: Trudy soveshchaniya po serebristym oblakam (Works of a Conference on Noctilucent Clouds), Vol. I. Tartu, 1959.
3. Dirikis, M.A.: Trudy soveshchaniya po serebristym oblakam (Works of a Conference on Noctilucent Clouds), Vol. III. Tallin, 1962.
4. Grishin, N.I.: Nekotoryye problemy meteorologii (Some Problems of Meteorology). Izdat. Akad. Nauk S.S.S.R., 1960.
5. Grishin, N.I.: Univ. obs. Oslo. Third Publication, 1933.
6. Stormer, C.: Astrophys. Norveg., Vol. 3, 1935.
7. Grishin, N.I.: Trudy VI soveshchaniya po serebristym oblakam (Works of the Sixth Conference on Noctilucent Clouds). Riga, 1961.
8. Witt, G.: Height, Structure and Displacements of Noctilucent Clouds. Tellus, Vol. XIV, 1962.

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